Title	Nature and derivation of glacial till in part of the Tweed basin
Author	Kerr, Robert J.
Qualification	PhD
Year	1978

THE NATURE AND DERIVATION OF GLACIAL TILL IN PART OF THE TWEED BASIN

ROBERT J. KERR

Ph.D. Thesis

UNIVERSITY OF EDINBURGH

1977.

In accordance with the University of Edinburgh Regulations for Postgraduate Study 2.4.15., I hereby declare that this thesis has been composed by myself and is entirely my own work.

CONTENTS

ACKNOWLEDGEMENTS

The author wishes to express his gratitude to the following:

to the Gas Council for permission to examine the pipeline section and to the many individuals who assisted with various aspects of measurement and sampling 'on site',

to Edinburgh University for provision of a research grant,

to many farmers throughout the Tweed basin for kind permission to sample freely in many parts of the study area,

to Dr. J.B. Sissons and Dr. J.A.T. Young of the Geography Department, University of Edinburgh, for advice, encouragement and valuable discussion,

to his long-suffering wife and parents for their active encouragement,

and to all other individuals who have assisted with various aspects of the preparation of this thesis.

ABSTRACT

Initial studies were associated with a gas pipe-line trench (average depth c. 2.3 m) cut obliquely across the Tweed drumlin field for 26 km west-northwest from near Coldstream (NT 858413). These studies include stratigraphy, stone-counts (50 sites in the "basal series" and 28 from intermediate levels), macro-fabric orientation analyses (29 sites), particle size and heavy mineral analyses (48 and 15 sites respectively).

Surface stone-counts were made in association with pipeline sampling, and counts of a finer size-fraction (100-160 mm) made on most basal samples. Surface stone-counts were also carried out away from the pipeline within the middle Tweed and Teviot basins, regional implications being interpreted in the light of relationships and patterns observed in pipeline-associated studies. Around Black Hill near Earlston, detailed erratics studies recorded changing concentrations of an indicator stone in surface tills, from which local variations in basal ice flow were inferred.

Deposition processes are considered and melt-out tills, often with associated sub-till fluvioglacial sequences are identified locally. Such tills, part of a suggested pattern of ice sheet stagnation, are not recognisable by the normal characteristics of ablation tills.

Variations in till character and composition are noted vertically within sections, and regionally in relation to changing geology. Increasing dominance of exotic Silurian erratics towards the surface of all sections and at increasing distances down-glacier of source, is interpreted in the light of ice stagnation. A threefold zonation is

suggested within any drift sequence, this zonation having been controlled by position in the glacier bed or basal ice immediately prior to stagnation. The development of individual zones varied locally with changing conditions at the glacier sole.

Geological, orientation and erratics evidence is also related to drumlin form and occurrence. Theories are offered on drumlin formation as part of the depositional sequence within the Tweed basin.

CHAPTER ONE

INTRODUCTION : GEOLOGY ; TOPOGRAPHY

The Region

The area of study lies south of Edinburgh in the Tweed basin. It is part of the Middle Tweed region lying between Melrose and Coldstream in a west-east direction, and stretching to the Teviot in the south. The northern limit approximates to a line running just north of Earlston and Gordon, south of Greenlaw and thence to Lennel Village some 2 km east of Coldstream (Fig. 1).

In many respects the area is well suited to such till studies as were undertaken, particularly questions of composition and derivation and the areal variations in these. This is mainly due to the particular alignment of the major geological groupings which for the most part exhibit a trend running obliquely across the direction of regional ice movement (Fig. 2). Differences between the variety of rocks included in these groupings are generally recognisable in the field.

Geological studies had to encompass a greater area than that outlined above, since knowledge of this wider area was necessary to an examination of the erratic content of till deposited by north-eastward moving ice. The geology examined below is therefore inclusive of all those areas that are likely to be represented in the till of the study area.

The Basis for Geological Studies

Although it is true that from time to time in recent decades particular facets of the geology of the Tweed basin have been studied in detail (e.g. Tomkeiff, 1945), the major survey of the area still looks back to much more dated material. The basic Geological Survey

FIG. 1. LIMITS OF THE STUDY AREA.

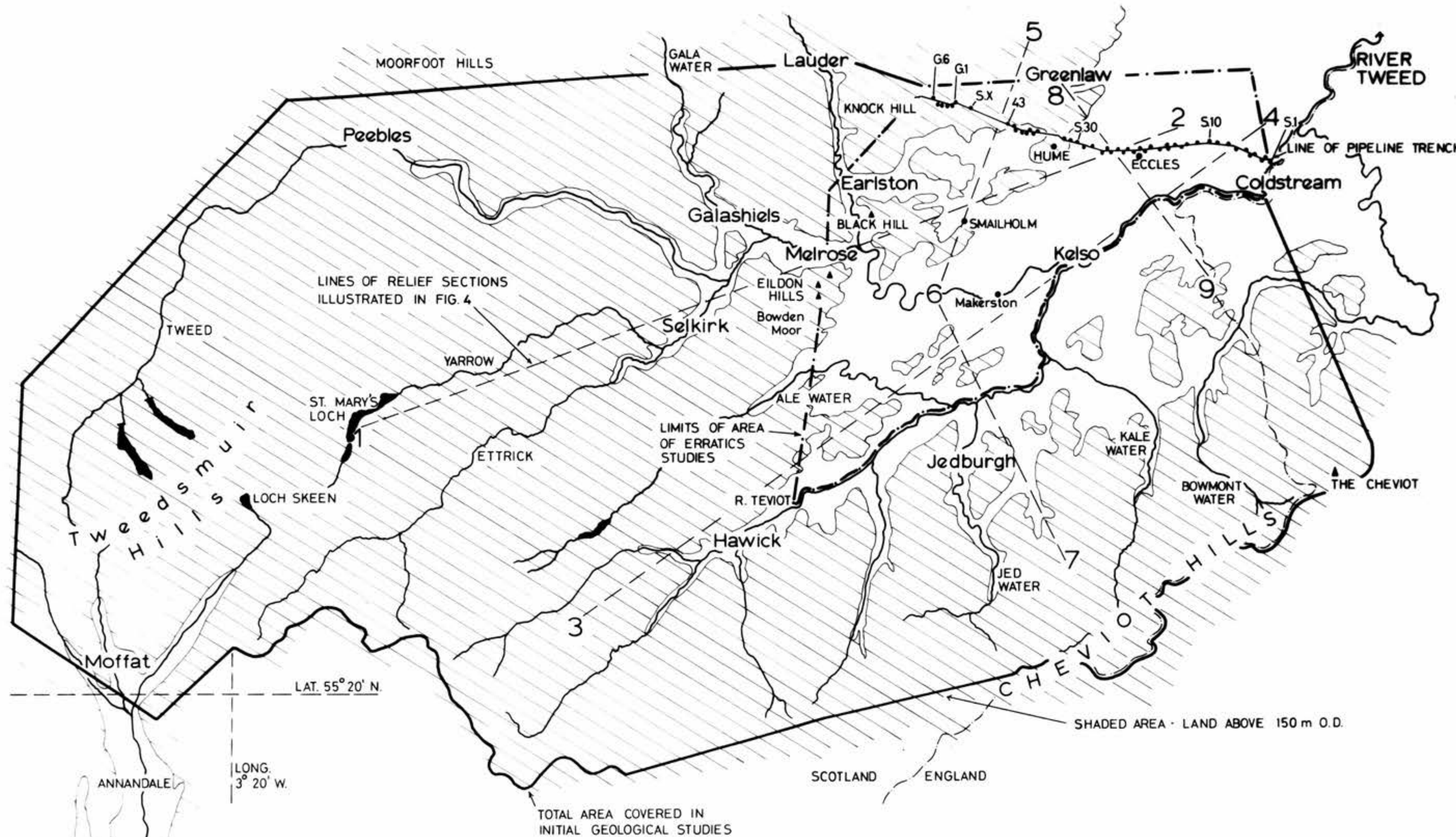
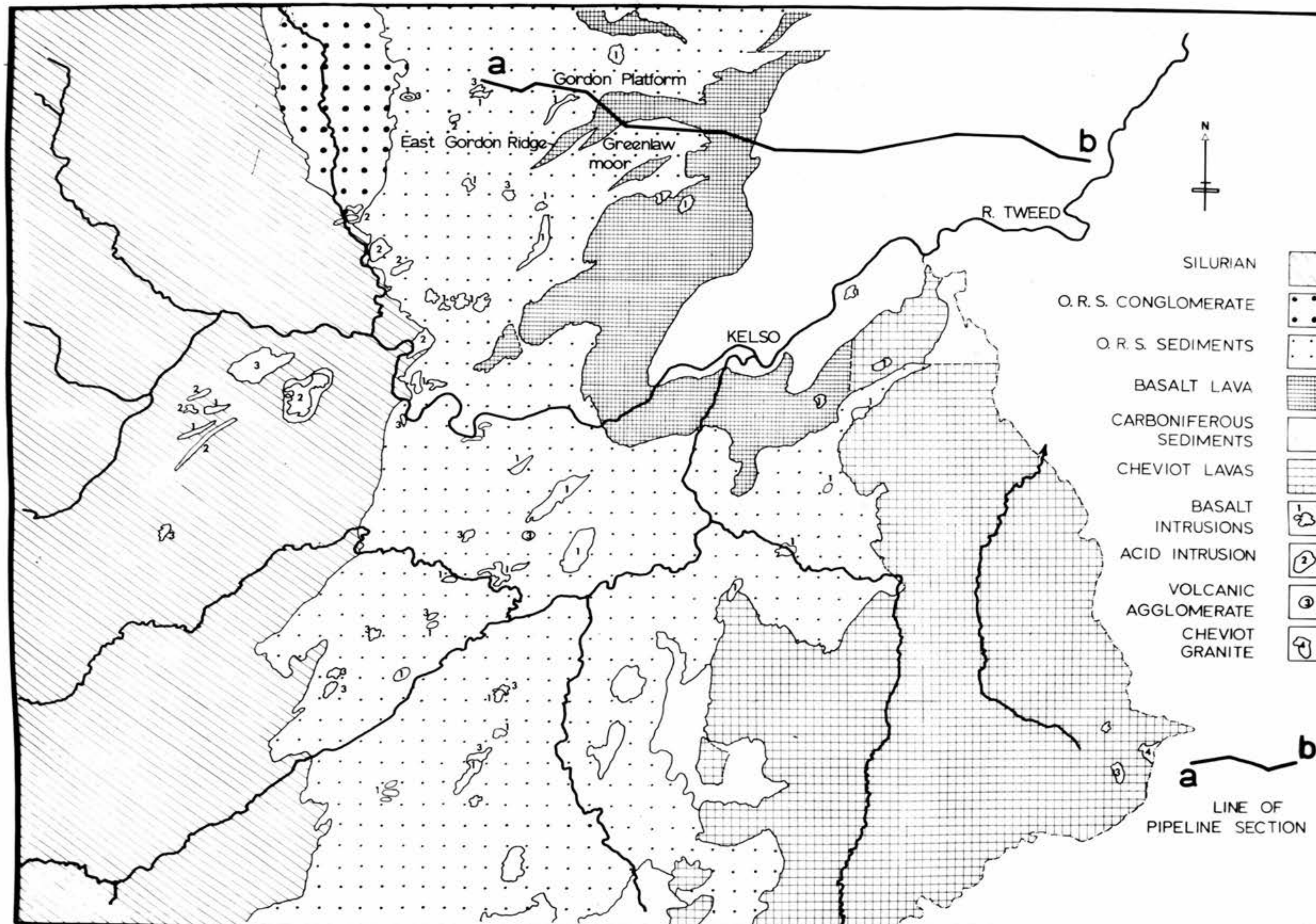


FIG. 2 GEOLOGY



work was carried out in the late 19th century. (The only comprehensive map published was compiled in the 1870's and is based on J. Geikie's work.) Much of this early work is commendably accurate and indeed Tomkeiff (1953) in his own work on the Carboniferous igneous groups found cause to comment on this. His own detailed work differed from Geikie's mapping only in minor classifactory details for the most part.

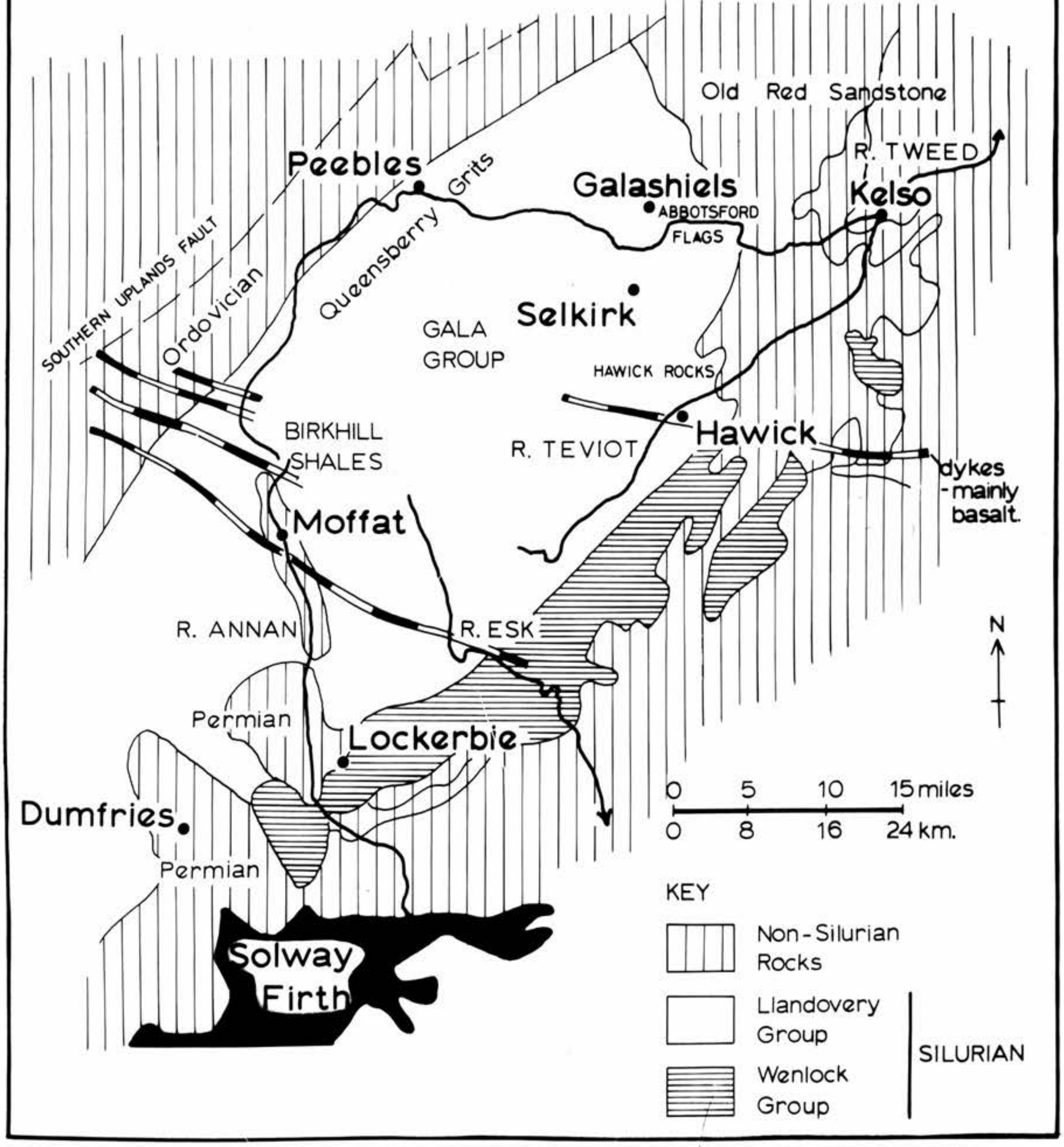
Accurate and admirable though much of this early work may be its inadequacies in areas with extensive drift cover must be recognised. The Carboniferous and Old Red Sandstone areas have, with few exceptions (e.g. Fowler and McGregor, 1937), had little information added to them since the initial survey. These are particularly difficult areas to study with their scarcity of outcrops, especially the Carboniferous area.

It also became apparent during various aspects of fieldwork that minor inaccuracies, or rather minor omissions, did exist in the original mapping. These were mainly detected in the occurrence of small plugs pipes or similar features or at least the evidence for the existance of such in areas where none were indicated in geological mapping to date. As later results will illustrate, the only evidence for the prescence of such features might be the sudden appearance in a stone-count sequence of appreciable percentages of a hitherto unencountered rock type. These intrusions, being generally small and local, might be considered to have little effect on the regional pattern of stone-count results. Their locally high percentages have the effect of appearing to lower the otherwise higher percentage of the major till constituent locally and thus will have an impact indirectly on the wider pattern.

Geological Sampling

Preparatory work to the author's till studies thus involved the collection of as fully representative samples of the various geological groupings as was possible in the field. The Silurian, the Carboniferous

FIG. 3 THE SILURIAN and its sub groups



lavas and the various igneous intrusives were relatively easy to collect and examine owing to their obvious prominence and more frequent bedrock exposure. The Carboniferous sedimentary rocks are relatively poorly exposed, as to a lesser degree are the Old Red sedimentary rocks. Despite this, a few valuable sections do exist in both. For example, such sections were found in the Carboniferous in the meltwater cuts of Wooden Dean (N.T. 742342) and the Leat Water (N.T. 813415), as well as in a few sites exposed by the R. Tweed. In the Old Red area valuable sites were examined in cuts of the R. Teviot and Kale Water in the region of their confluence and at Lanton Quarry, west of Jedburgh. Examination of these sites, allied to studies of the limited available literature, gave the basis for field recognition of erratics from these groups.

GEOLOGY AND RELIEF

The Silurian rocks

Although barely impinging on the actual till-study area, the Silurian rocks form one of the major groupings that must be considered for they lie immediately up-ice of the study area and are of considerable extent (Fig. 2). Silurian rocks stretch to the west across much of the breadth of southern Scotland. They are bounded in the east by a line that just crosses the course of the Leader Water as it flows south from Earlston to the Tweed. This boundary swings south-west, passing a few km east of Hawick before turning again to the west to lie uncomformably against Upper Old Red Sandstone rocks and then against Lower Carboniferous rocks.

As can be seen on Fig. 3, the Llandovery group is the more extensive of the two major Silurian groups in south-east Scotland. The base of the Llandovery co-incides with the northern edge of the Silurian belt where it adjoins Ordovician strata. In the south the Hawick rocks a sub-group of the Llandovery, pass comformably beneath the Wenlock, the other major Silurian group. The Llandovery is represented by several contrasting types of rock with two main sub-groups recognised: the Gala group and the Birkhill Shales (Pringle, 1948). So quickly do the thinner Birkhill Shales pass laterally into greywackes, grits and lesser shale bands, that differentiation between the two groups except in a chronological sense, is of little significance in a study such as this as far as practical aspects of fieldwork are concerned. It does, however, provide a useful basis on which to discuss the variety of rocks existing within the Silurian.

The Birkhill Shales tend to be more prominent farther westwards, notably lying near the surface in the Moffat area for instance. Farther east the upper shales tend to be replaced by greywackes, flags and other shales, whilst in the lower divisions greywackes become interbedded with black shales. In other areas grits and greywackes become intercalated.

The other major sub-group of the Llandovery, the Gala Group, tends to be dominated by flags and grits with bands of greywackes and shales. Much of its central area is occupied by coarse-grained greywackes with bands of conglomerate. There exists greater complexity than might be envisaged from such a description however. To illustrate this some of the sub-groups within the Gala Group can be considered. For example, the Hawick Rocks already mentioned, have their main outcrop south and east of Selkirk although infolds can be found more than 16 km to the north-west. They are dominantly argillaceous rocks consisting of grey, green and red shales, brownish flagstones and grey-brown or yellow-brown greywackes. They also contain occasional grits and conglomerates. Another sub-group, referred to as the Abbotsford Flags (Pringle, 1948), occurs mainly in a belt between Melrose and Galashiels and consists dominantly of brown flagstones with shales and mudstones. Immediately north-west of this group lie the Queensberry Grits. This sub-group probably forms the major component of the Silurian immediately up-ice of the study area. It is composed of massive grey and red-brown grits and greywackes with local bands of conglomerate or shale; the latter are usually red, green or grey in colour.

The other major Silurian group, secondary in this case to the larger Llandovery, is the Wenlock Group. This forms a belt in the south of the Silurian area (Fig. 3). Variety can be recognised within this group with a basic two-fold division evident (Pringle, 1948). The upper group, referred to as the Raeberry Castle Group, comprises various shales, usually green in colour, with thin-bedded greywackes and occasional grits and conglomerates. The lower and thicker group, the Riccarton Group, comprises conglomerates, grits and shales, often in thick bands.

This reference to upper and lower divisions is misleading to some extent in that such a description is of limited application over much of the Silurian particularly for the purposes of this study. The intense folding and subsequent erosion of the Silurian strata often mean that quite locally considerable variety may be represented in surface exposures.

It is the grits and greywackes however with their near ubiquitous distribution within the Silurian and with their considerable variety even within sub-groups, that will be shown to be of particular significance for the tills of the Tweed basin, especially in the petrology of the till macrofabric. It is sufficient to note at this juncture however, that despite the apparent complexity of the Silurian rocks, varieties of greywackes, grits and shales predominate. The net result as it affected macro-petrological studies of the tills was that it was not possible to attribute Silurian erratics to any particular area of occurrence within the Silurian groups.

To complete the consideration of the Silurian it is necessary to refer to some aspects of the relief presented by these rocks. Immediately west of the Leader Water summits range from 200 to 300 m O.D. in the Gala Uplands with the range of altitude locally reaching 150 m or more, notably in the major valleys. The general aspect is of not too steeply rolling marginal hill land increasing in height westwards. A similar landscape exists to the south-southwest of this in the Bowden-Lilliesleaf areas where summits reach 250 m O.D. and local relief is generally low. Ice-moulded bedrock and roche moutonnees are characteristic of the higher parts of the area, which exhibit outcrops of various shales and greywackes.

Farther west however the land rises appreciably to reach over 800 m in the Tweedsmuir Hills. Local relief can reach 300 m or more. South-east towards Hawick relief is generally less although summits reach over 300 m O.D. Northwards towards Peebles summits consistently reach 600 m O.D. with deep and steep-sided valleys.

On the almost plateau-like area between Yarrow and Teviot at heights of about 250 to 360 m O.D., the work of north-eastwards moving ice was assisted by the fact that the dominant bedrock grain of the area is southwest-northeast. A series of long ridges of rock, often with partly drift-filled intervening hollows, parallels the ice trend in these areas. This "corrugated relief" (Ragg et al, 1960) is seen over much of Bowden Moor for example. It is very common among the Hawick Rocks where bands of fresh well-cemented greywackes show a relative resistance to erosion to stand as ridges. Elsewhere the Silurian is associated with the characteristic rounded summits of the familiar Southern Uplands scene with scanty till cover on the higher areas.

The main valleys of Tweed, Teviot, Ettrick, Yarrow, Gala Water and Ale Water tend to be confined within steep walls of Silurian strata with occasionally some degree of till or solifluction deposit at their base. Such deposits have often been re-worked by meltwaters and incorporated in outwash flats (Ragg et al., 1960). The valley floors tend to be flattish and broad with terrace development particularly in wider areas. Fluvioglacial deposition is apparent locally, especially at these wider parts, as at the confluence of Tweed and Ettrick and towards the edge of the Silurian area in the major valleys. Certain north-south tributary valleys are characteristically asymmetrical with steep west-facing valley walls but gentle east-facing sides.

<u>The Lower Old Red Sandstone Volcanics</u>

These are a spread of dominantly andesitic lavas forming part of the Cheviot hill group. Although playing a relatively minor role quantitatively in most stone counts in the area of the Tweed basin, their marginal position to the study area is nevertheless of some importance in relation to regional and local ice movement.

As part of the Cheviot Volcanic Series, the lavas extend from some 6 km south-east of Kelso to just east of Morebattle and from there swing round to a point some 7 to 8 km east of Jedburgh (Fig. 2). South and south-east of Jedburgh small isolated areas of lavas crop out. The lavas range in elevation from about 160 m O.D. at their north-western limit on the edge of the Cheviot foothills, to over 450 m O.D. in several summits to the south-east.

Three main groups have been recognised within the lavas (Pringle 1948). These are a) glassy pitchstone - like andesites

b) oligoclase trachytes

c) augite - hypersthene andesites

The rocks, which are characteristically porphyritic, exhibit a considerable variety of colour with red, brown, purple, grey and black being found. Colour is controlled to a large extent by the degree of weathering.

The Upper Old Red Sandstone Sediments

East of the great extent of the Silurian rocks, a considerable belt of sediments of Upper Old Red Sandstone age is encountered. These rocks occupy a tract of undulating country swinging south through the Greenlaw area to a point south of Jedburgh. Here the outcrop narrows to a faulted strip running through to Langholm to the south-west (McGregor and Eckford, 1948). North-west of Earlston in the Leader valley, conglomerates are particularly conspicuous, and, with some sandstones, form a narrow tongue up the valley. Outlying patches of Old Red sediments are to be found around the Eildon Hills near Melrose and between Melrose and Selkirk, testifying to the former greater extent of this group. An example is Tudhope Hill east of Mosspaul (Fig.7 ; Pringle, 1948). In the main Old Red group, sandstone is the dominant rock type although locally this may be superseded by conglomerate as noted in part of Lauderdale and on Greenlaw Moor. The conglomerates are coarse basal types, generally bright red in colour and consist mainly of pebbles or cobbles of greywackes. Locally the conglomerates are interbedded with sandstones.

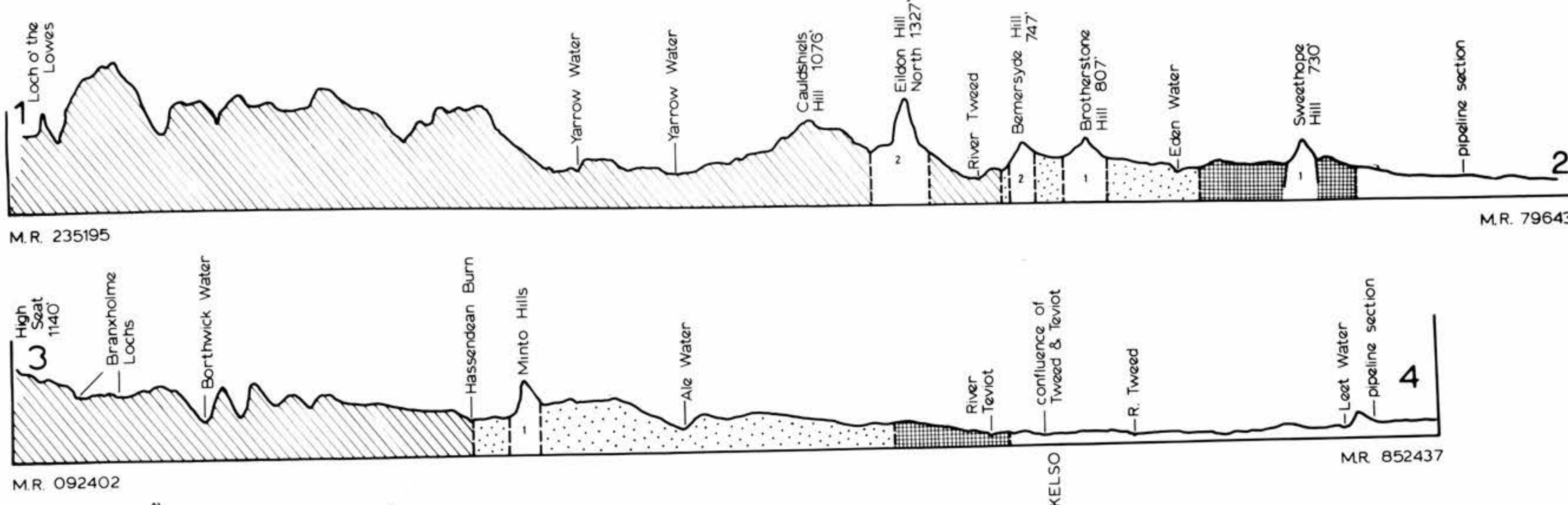
South and east of the conglomerates are found the main sandstone groups consisting mainly of red and yellow sandstones with interbedded red or purplish brown shales and marls (Fowler and McGregor, 1937). The sandstones are comparatively soft and contain high percentages of cementing silica (Ragg et al., 1960). The shales and marl, which generally impart a finer texture to soil or till, often contain much material of the silt and clay grades. For the most part however, little is known of the petrology of the Old Red sediments, especially the shales and marls.

As with the Silurian rocks, the author did not generally find it possible to attribute particular rock types to specific localities within the Old Red area. This was mostly due to the dominance of sandstones as erratics and their ubiquitous distribution throughout the Old Red area. Variety was noted, particularly in terms of colour and grain size, but this does not appear to change according to any particular areal pattern.

The relief of the area might be described as gently rolling but with a major relief being imparted by various igneous intrusives. The Old Red formations generally form the lower ground. Drumlinoid forms are apparent in the drift of the area although the crag and tail formations produced by these igneous bodies are appreciably more imposing. Examples of these are the trachytic bodies of Black Hill and White Hill near Earlston or the basalts of Redpath and Brotherstone Hills. Black Hill for instance, rises over 200 m from the valley of the Leader Water just south of Earlston and has a tail of over 3 km in length. These igneous bodies therefore tend to control the relief of the area rising to altitudes as great as 313 m O.D. in the case of Black Hill, 268 m for Redpath Hill, 297 m for Knock Hill and 227 m for Bemersyde Hill (Fig. 5). With the low ground of the area only at about 150 m O.D. these hills form prominent features.

The Carboniferous Extrusive Basalts

East again of the Old Red sediments and forming generally higher ground running across the direction of ice movement, a spread of olivine-basalt lavas known locally as the Kelso Lavas or Kelso Traps occurs. These lavas can be traced from the Duns area to pass east of Greenlaw and thence across the Tweed some 5 km west of Kelso (Fig. 2). The belt then swings east past Kelso to run some 10 km down valley. A narrow arm also extends south from near Kelso almost to the Kale Water. The major development of the lavas however is north of the Tweed in the Stichil-Smailholm area.



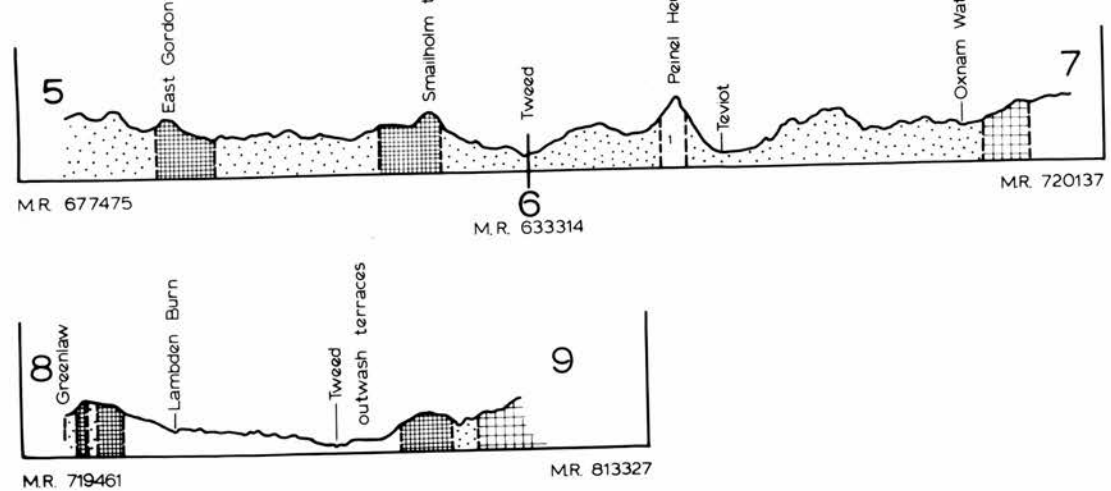
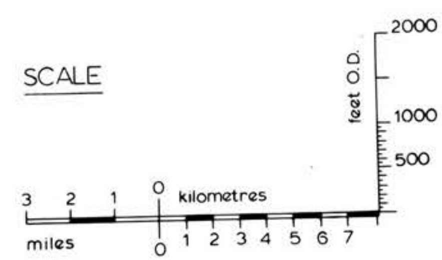


FIG. 4 Relief Sections

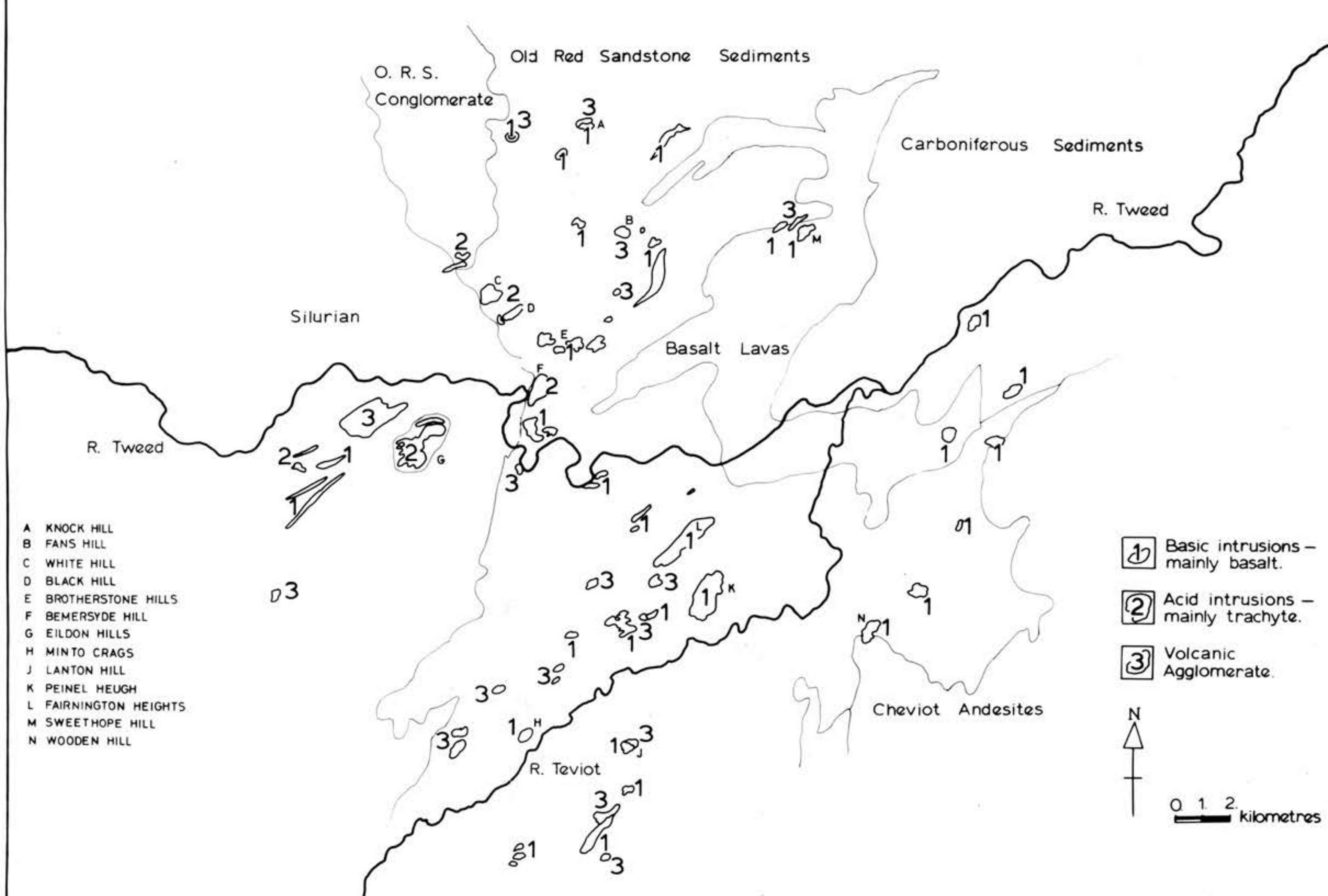
(See fig.1 for lines of section, fig 2 for geology key)

SCALE



VERTICAL EXAGGERATION : 10·56

FIG. 5 Distribution of major intrusions



Although some of the lavas are intercalated at their base with baked Upper Old Red sediments (Eckford and Ritchie, 1939) the great outpouring took place at the beginning of the Carboniferous. (The lavas underlie the Cementstone group of the lower Carboniferous). The lavas and the fringing Carboniferous sediments occur in a northeastwards-pitching synclinal basin, the lavas thinning out in this direction. The maximum thickness of the lavas is over 300 m.

They are dominated by olivine-basalt although some variety does exist. A common distinction is made, for example, between macroporphyritic and microporphyritic (Tomkeiff, 1945). The lavas are characteristically described as being considerably decomposed yet fresh outcrops may be found locally. Calcite veining and brecciation are other local characteristics. In hand specimens, dark red pseudomorphs after olivine are most conspicuous, with felspar phenocrysts up to 1 cm long in the macroporphyritic variety. Fresh rocks tend to be bluish-grey in colour. The general colour of the more prominent types of altered rocks may be greenish-grey, lilac, purplish or reddish for the most part.

The lavas flowed from numerous orifices and although there is evidence for some of these being present within the lavas themselves (e.g. at Smailholm Tower), it is suggested that the sites of the vents are marked by numerous necks filled with volcanic agglomerate (e.g. Fans Hill) or by basaltic plugs (e.g. Mellerstain Hill) that pierce the Upper Old Red Sandstone sediments along the line of the lavas (Tomkeiff, (1953). It has also been suggested that a group of large agglomerate necks between Melrose and Selkirk may mark the sites of vents associated with these lavas (Pringle, 1948).

The relief produced by the Kelso Traps tends to be higher than much of the Upper Old Red Sandstone and Lower Carboniferous sediments

(Fig. 4). Erosian by ice has been intensive on the lavas and rock exposures are frequent in the ice-moulded topography. In the Hume-Stichil-Smailholm areas the lavas reach altitudes in excess of 200 m O.D.

The Igneous Intrusive Bodies

The igneous intrusives are mainly basalts, although several agglomerate necks and some important acid intrusions are also found. Tomkeiff in particular has studied the differentiation and classification of the various basic rocks (Tomkeiff, 1945, 1953; also Eckford and Ritchie, 1939) while the acid intrusions, believed also to be of Carboniferous age, have been examined by McRobert (1914).

Tomkeiff based his classification of the intrusive basalts upon that used by McGregor (1928) in a study of Scottish Carboniferous olivine-basalts, related in that instance to the Midland Valley of Scotland. Six main types are suggested by a classification based on the size and composition of phenocrysts. Differences in chemical composition between the various types are very small but this gives a division, albeit as Tomkeiff admits, to some extent rather an arbitrary one, as follows:

	PYROXENE RICH	INTERMEDIATE	FELSPAR RICH
MACROPORPHYRITIC	Craiglockhart Type	Dunsapie Type	Markle Type
MICROPORPHYRITIC	Hillhouse Type	Dalmeny Type	Jedburgh Type

(Within the Kelso lavas themselves are found examples of the Jedburgh type, generally in association with the Markle type, and also examples of the Dunsapie type in association with the Dalmeny type.)

The basic intrusive bodies have not been found among the Carboniferous sediments but they have been found within the Carboniferous lavas and also within the Old Red sediments where they have their major distribution (Fig. 5). Their locations suggest intrusion soon after the extrusion of the lavas. Examples of the six types illustrated above are not only to be found scattered over the lava and Old Red areas but can even be found side by side within individual bodies. A few examples of the distribution of some of these will illustrate this point. e.g.

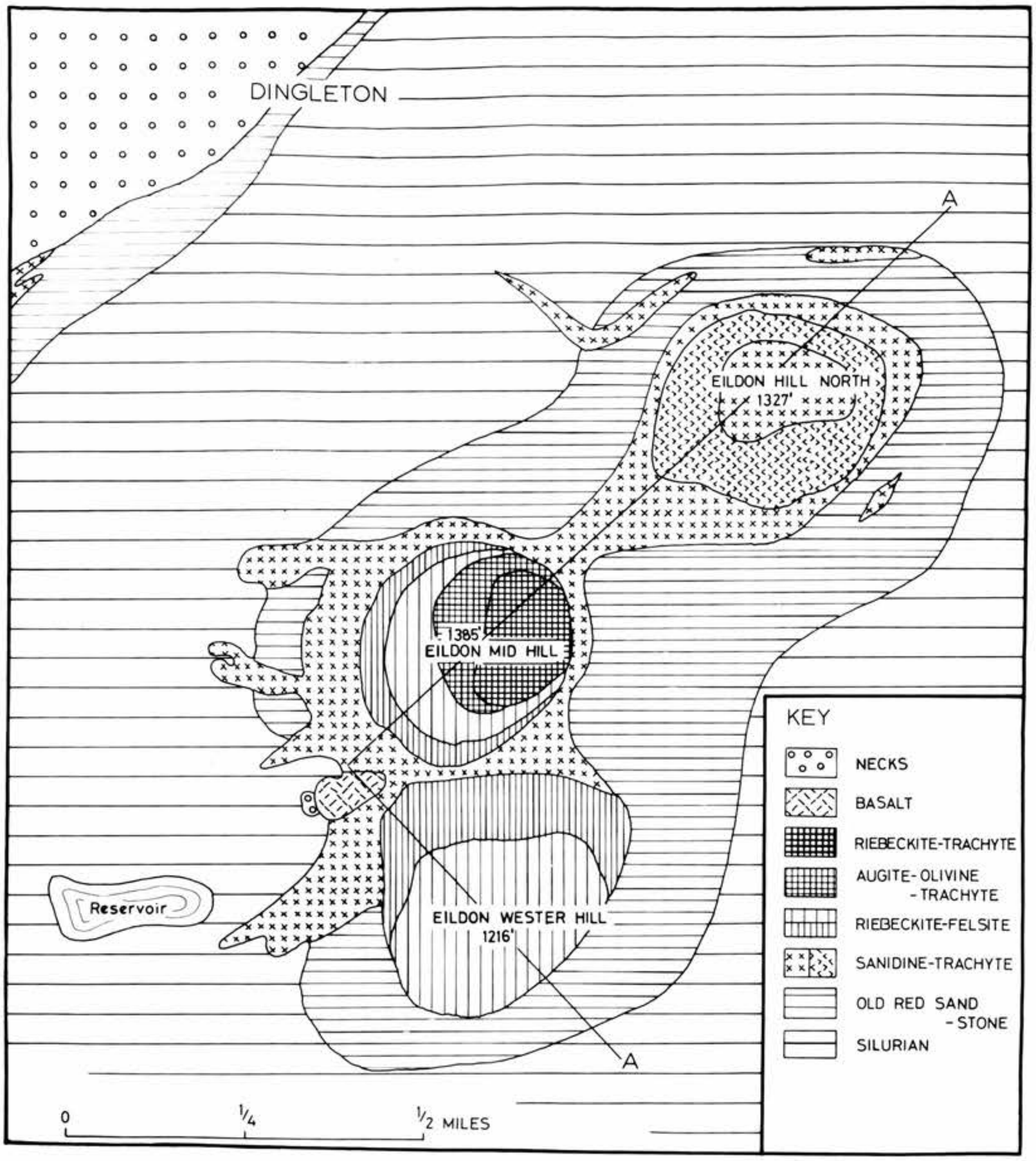
The Dunsapie Type	:	Hareheugh Craigs	(Composite plug) K.a.R.?
The Dalmeny Type	:	Sweethope Hill	(Plug within lavas)
		Blinkbonny Hill	(Composite plug)
The Markle Type	:	Knock Hill	(Plug)
		Hareheugh Craigs	(Composite plug)
		Brotherstone Hill	(Plug)
The Jedburgh Type	:	Brotherstone Hill	(Plug)
Olivine-dolerite	:	classified with the Jedburgh type this includes Blinkbonny and Brotherstone Hills.	

(after Tomkeiff, 1953)

The felspar-rich basalts including the olivine-basalts form over 65% of the total mass of the basic intrusions.

The acid intrusions occur among rocks of Upper Old Red Sandstone and Silurian age. Their age is to some degree a matter of inference but they are generally classed as Carboniferous. The main group as far as this study is concerned, is that dominated by the Eildon Hills and the bodies to the north-northeast of this. These are mainly varieties of trachyte. In the Eildon mass considerable variety exists (Fig. 6) although nearly all rocks are recognisably of a general trachyte-felsite nature. The three bodies of Bemersyde Hill, Black Hill and White Hill are of differing varieties on this theme also. Bemersyde Hill is identified as non-porphyritic quartz-trachyte, Black Hill as porphyritic quartz-riebeckite-trachyte and White Hill as soda-orthophyric-trachyte (McRobert, 1914). Another smaller body lying immediately north-west of Earlston is of uncertain type. Field examination of these outcrops

Fig. 6 Eildon Hills — Geology



Geological Section Along A–A (After Lady McRobert, 1914)

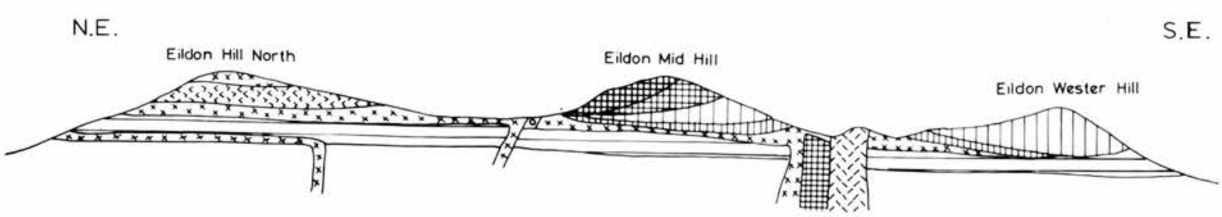
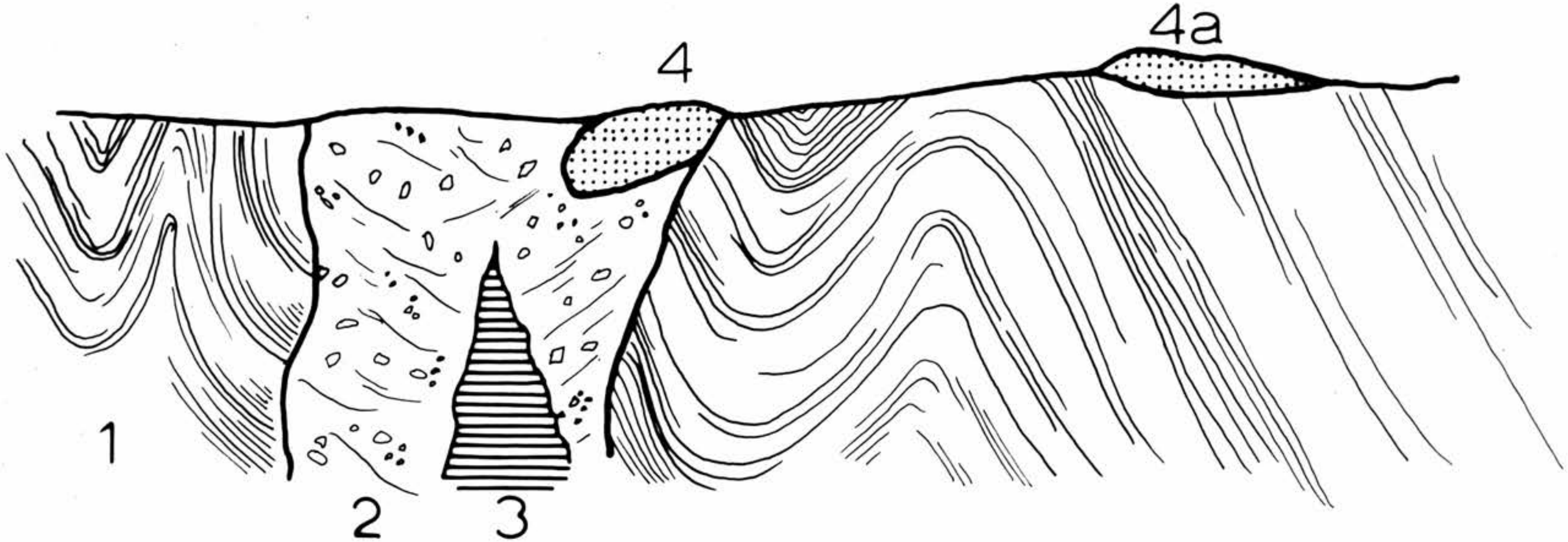


Fig 7

Old Red Sandstone outlier near Tudhope Hill



1. Silurian
2. Agglomerate
3. Basalt intrusion
4. O.R.S. mass in vent

4a. Upper O.R.S. outlier

by the author revealed considerable similarities in appearance between the various rocks, yet at the same time showed considerable variations in some details within single outcrops. These variations were particularly in terms of colour, crystal size and to some degree in structure. Any weathering of the rocks tended to further complicate the picture. The general similarity however, enabled erratics to be classified in a general trachyte-felsite group. The net result was again one of difficulty in attributing individual erratics to any particular outcrop except in cases such as the riebeckite-felsite and the augite-olivine-trachyte of the Eildon group or when sampling was in close proximity to an outcrop.

Similar limitations apply to the basalt intrusions. Much of Tomkeiff's work involved fairly detailed mineralogical examination on fresh 'type'-samples of the various basalts. Tomkeiff confessed to ignoring certain minor variations from his classification even though most were generally close affiliations to classified types. These occurred even within single outcrops. Accordingly the author found that macro-petrological work on till especially when potentially involving weathered or small fragments, could not reasonably permit differentiation of erratics from the different basalt bodies. A further complication in this is that in many cases similarly classified outcrops may occur on the same line of ice movement or within a few kilometres of it. This fact, coupled with the widespread distribution of the various types as illustrated above, makes them of limited value for any detailed work on erratics.

On this question of basalts and their recognition, it has been suggested that a distinction between weathered (meaning specifically chemical alteration) and un-weathered basalts could serve as a valid distinction between the great spread of extrusives of the Kelso Traps on the one hand and the many individual intrusive basalts on the other (Tomkeiff, 1953). Field experience, notably detailed examination and sampling of both types, shows that for the purposes of such a till study as was undertaken such a differentiation could not always be relied upon. For example, a very great variety in appearance exists within the lavas often very locally (e.g. Hune quarry), and relatively un-weathered basalts are by no means uncommon. Another complication is the existance within the lavas of vents (plugs) e.g. Smailholm Tower area, that exhibit types of basalt more analagous to the intrusives than to the main lava body. Finally it should be added that weathering to varying degrees, if only some degree of staining, is not uncommon among many of the 'fresh' basalts, especially fragments incorporated in tills.

The Lower Carboniferous Sediments

The crescent-shaped mass of the Kelso Traps encloses to its east Lower Carboniferous sedimentary rocks that cover much of the lower Tweed basin and stretch across the Tweed into North-East England. On the Scottish side of the river the rocks occupy the low-lying Merse of Berwickshire from Kelso north to Duns and east towards Berwick.

In the west and lying immediately above the Kelso Traps is the well-known local rock, the Carham Stone, a chiefly magnesian limestone of the Cornstone group. This occurs generally in thin layers. The overlying sediments consist of variously-coloured shales with many bands of sandstone and some seams of impure limestone and cementstone with gypsum partings. The sandstones of this Cementstone group vary from thick red beds to numerous less thick yellow and white beds. The total thickness of the group is estimated to be 750-900 m at the maximum. The beds are thought to represent estuarine deposits of mud, silt and sands deposited on flats near sea level (Goodchild, 1904 ; Pringle, 1948).

Information on the surface occurrences of the different rocks is limited and the author's examination of such outcrops as were available was not enough to lead to the emergence of a pattern. Consequently Carboniferous sedimentary erratics could not be attributed to specific areas within the Carboniferous region.

The abundance of sandstones in the Lower Carboniferous strata and their consequent representation in erratic counts was a factor that necessitated some reliable means of distinguishing these from sandstones derived from the Upper Old Red Sandstone formations a short distance up-ice (as little as 2-3 km in some cases). Both types are largely of quartz and felspar with subordinate mica and other accessory minerals. Any biotite present is usually much altered. As regards colouring considerable varieties do exist in both. Reds, red-browns and pinks predominate in the Old Red formations but with buffs, yellows and white also present. The Carboniferous has a predominance of yellows or grey-buffs but pinks, reds or greens occur locally. The problem of distinction is alleviated to some extent in that it is generally the white and yellow varieties that occur nearer the surface in the Carboniferous. Both Old Red and Carboniferous sandstones also appear to be very susceptible to glacial abrasion as will be shown by later stone-counts, so that erratics tend not to occur at any great distance down-ice of their source. Where erratics were found that were potentially either Old Red or Carboniferous, the following factors could help to distinguish the two varieties although all are not readily applicable under field study conditions.

a) The Old Red sandstones contain much less disseminated mica, muscovite usually being inconspicuous and biolite often absent. On the other hand the latter may be very conspicuous in Carboniferous varieties.

b) The Old Red types show an absence of dark mica-rich films that locally emphasize false bedding in the Carboniferous varieties.

c) The Old Red varieties contain, especially in coarser layers, wind-rounded quartz grains with very often evidence of secondary quartz growth. These are occasionally detectable using a hand lens.

d) Especially in coarser layers the Old Red types show greater proportions of quartz in relation to felspar.

e) The Old Red varieties do not have the lenticular bands of dark shale breccia that are often seen in the Carboniferous.

f) The Old Red shows no evidence of carbonised plant debris though this is not uncommon in Carboniferous exposures.

Colour and the prescence or lack of the different forms of mica were found to be particularly useful factors in the recognition of erratics from the different groups in the field.

The relief of the area of the Carboniferous sediments is dominated by drift forms, especially drumlins. Bedrock is generally covered by extensive glacial drift often to considerable depth. Areas of shallow till do occur and an example of this is to be found in the ridge of green micaceous sandstone some 2.5 km east of Hune village (N.T. 732420). Here the till is little more than one metre deep in places.

The area is low lying (Fig. 4), falling to 30 to 45 m O.D. on the terraces of the Tweed at Kelso, and to about 30 m O.D. and less on similar features near Coldstream. North of Kelso the land rises gradually onto the higher ground of the Kelso Traps at 150 to 200 m O.D. East of this, altitude falls off down the Merse so that by some 5-6 km north of Coldstream the crests of the highest drumlins generally reach less than 95 m O.D. Local relief is almost totally a factor of drumlin height, aided by a few deep meltwater cuts or generally small post-glacial stream incisions. Drumlins in the study area trend dominantly in a north-easterly direction, becoming more easterly in the Coldstream area.

The drumlins can vary considerably in size quite locally. Drumlinoid forms in the Old Red area tend towards massive crag and tail formations arising from the igneous intrusions, while in the area partly underlain by basalts to the north and west of Kelso some very long drumlins are found. These possibly again suggest some bedrock control. Even in these areas smaller drumlinoid forms do occur but more rarely. In the lee of the Kelso lavas, tail-like forms are again noted but farther onto the Carboniferous bedrock area regional size variations do not emerge. In general Tweed drumlins tend to be long and wide rather than of great height and features are usually over one kilometre in length. Exceptions are frequent however with several shorter steep-sided features existing. In addition, massive complex drumlinoid features may occur with superimposition of one or more drumlins on top of, or on the flanks of another (e.g. N.T. 777397, just west of Birgham village). In terms of actual heights, even such features as this may not reach 35 m from crest to inter-drumlin depression. The drumlins in the Carboniferous area are below about 15 m in local height except for a few larger, more imposing features, where in many cases some degree of bedrock control is suspected.

The Quaternary History of the Area.

This brief description is intended to serve as a background to the evidence presented in chapters 2 to 9. Little detail is available in the literature regarding the glaciation or de-glaciation of the study area and many opinions expressed here are necessarily those of the author. Many ideas touched on will be discussed more fully in the final chapter.

Early geomorphological description was often incidental to studies of the solid geology and consequently of limited detail. In 1895 Gunn and Clough recorded a depth of 31 m of till in a hollow between drumlins to the south-east of the study area. In 1930 a boring was made in a similar site within the study area (N.T. 742426) and 15 m of till was recorded (Manson, 1933). Only one till has been recognised in this eastern part of the study area examined by these early workers.

Until quite recently the evidence in the literature suggested a re-advance stage as being recognisable in the Tweed valley. Carruthers et al. (1932) recognised an extensive belt of sands and gravels east of the Cheviot massif as representing a moraine formed along the southern edges of a Tweed ice mass. Charlesworth (1957) pointed particularly to extensive fluvioglacial deposits lying south of Coldstream and Cornhill and referred to these as "moraine ridges". Sissons (1967) interpreted these deposits as possibly being associated with his so-called Aberdeen-Lammermuir re-advance stage in the Tweed basin. This envisaged an ice front lying across the Tweed valley just beyond Berwick.

Subsequent studies have suggested that this is unlikely. It appears, for example, that Charlesworth's "Cornhill Kettle Moraine" is the result of disintegration and stagnation of ice on a massive scale and many of the large morainic ridges, referred to by Charlesworth appear to have been deposited in large ice-walled channels under possibly open conditions (Sissons, unpublished). The significance of this hypothesis will be recognised later in relation to the deposits described in chapter two. Sissons (unpublished) in detailed mapping and examination of the Tweed drumlin field and its fringes, found no evidence of any limit or stage of any kind in the lower Tweed valley. The drumlin pattern completely disregards such a possibility and swings round without interuption into North-East England and assumes an almost southerly direction. It seems that no real evidence of any re-advance stage exists between the small moraines high in parts of the Southern Uplands and the limits discussed by such as Penny and Shotton as far away as Flamborough Head in Yorkshire. Fig. 7a shows this last ice movement across the area based on the evidence available.

The question of an ice limit can be of particular importance when considering a factor like ice thickness but a brief discussion of this question will point out the difficulties involved. Knowledge of the ice thickness at the period of drumlin formation would be particularly relevant. In this however there is a basic difficulty in that it is not readily apparent at what stage of ice advance or decay the drumlins were formed. Even with the proviso that there must have been active ice there are still many possibilities. They may have begun forming during ice advance at the maximum or at the final stages as ice flow began to slow down. Alternatively formation may have occurred to varying degrees during all these stages. (This question will be discussed more fully in a later chapter)

Work on a physical/mathematical basis in determination of former ice sheet thickness using analogies with present day examples would give very high figures for the Tweed ice (in excess of 2000 m even). While it can be recognised that ice in the Tweed valley must have attained considerable size and power to rise over fairly high mountain areas from the dispersal centres in central and western South Scotland (Fig. 7a), this does not have to be of the order of 2000 m. Models and formulae of any kind must have their basis in a simple type example of any particular phenomenon, i.e. in this case a single ice sheet with one great area of collection and dispersal, Such a hypothesis when applied to Scottish ice reaching Flamborough Head is seen to be inadequate and misleading. Several centres of dispersal were responsible for the ice which eventually reached this southern limit and it cannot be treated simply as one ice sheet. Ice streams flowed from the Forth and Tay valleys in Scotland as well as from the Tweed and ice also passed through the Tyne Gap from the Solway and Lake District areas.

Ice would not therefore have to be of the thicknesses envisaged by the simple mathematical model based on gradient formulae.

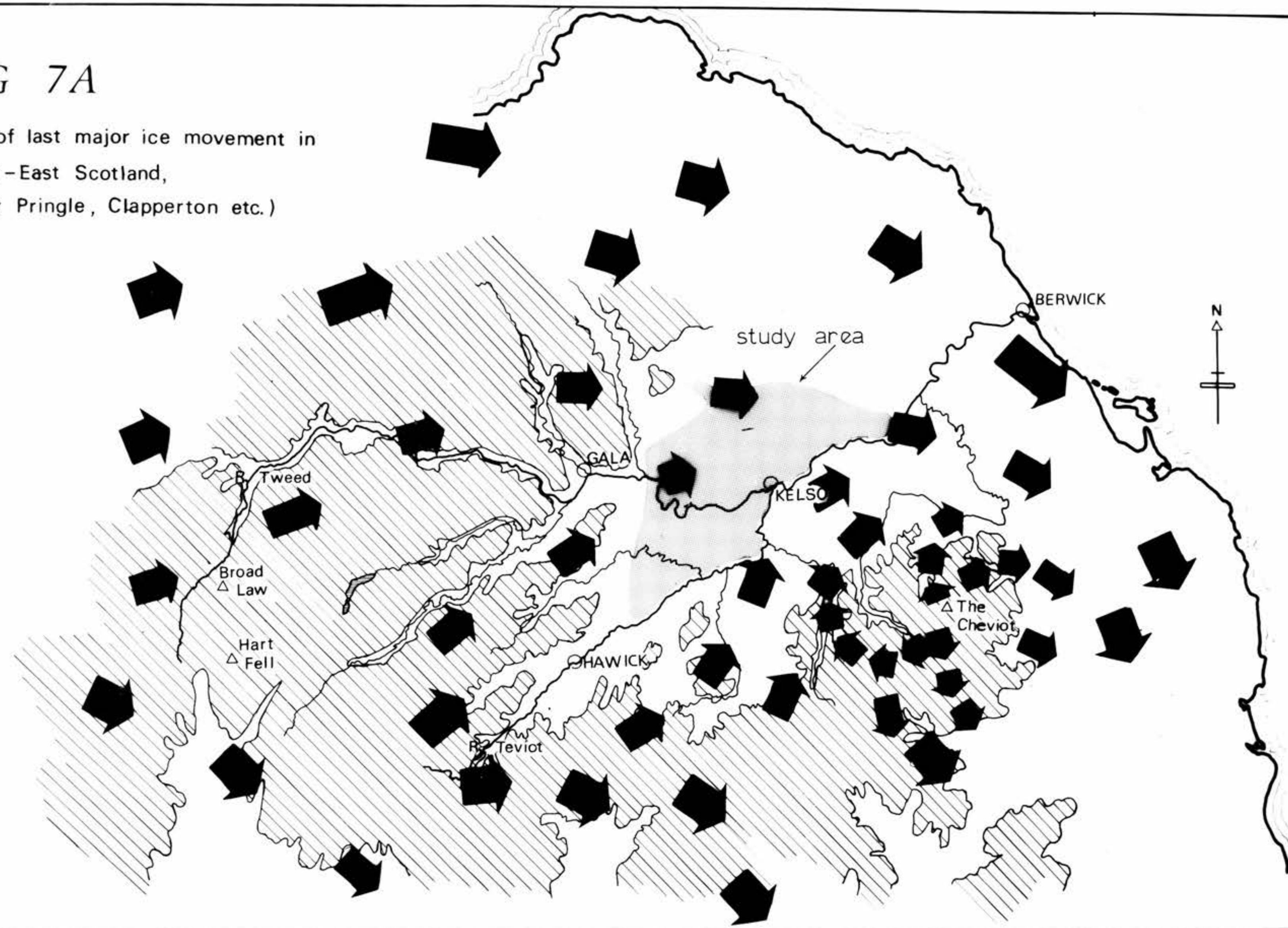
Even within the Tweed ice there are three major areas of dispersal influencing ice-sheet movement and size (Fig. 7a); the Merrick-Cairnsmore of Carsphairn area, the Broad Law-Hart Fell area and the eastern Cheviot Hills including the Cheviot massif itself. A particularly relevant point in considering the dimensions of the Tweed ice is the existence and apparent survival of the Cheviot ice-cap. Clapperton (1970) has pointed out for example that above about 300 m on the Cheviot massif only local igneous erratics are to be found and it appears that this area survived as a centre of dispersal during the last maximum glaciation. Clapperton (1968) also noted that on the north-east part of the massif ice from the south-west encroached to a maximum altitude of 366 metres. Examples from Antarctica today suggest that survival as a higher area of collection and dispersal is still possible after over-riding by exotic ice but this does not appear likely in the Tweed area for a marked and fairly sharp deflection northwards of ice in the area around Jedburgh is indicated by striae and ice moulded forms. It seems rather that the ice sheet was not thick enough to engulf the local ice dome.

The drumlins and other drift forms of the till study area have already been described in the discussion of the solid geology and little need be added to that at this stage. Several drumlins in the area east of Kelso appear to be composed at least partly of water-worn gravels in a sandy matrix. Clapperton (1971) pointed out that these may have been formed by ice moving over earlier fluvioglacial deposits. This question is examined in chapter two in relation to examples noted in the section studied by the author.

Fluvioglacial moraines are less conspicious in the immediate study

FIG 7A

Map of last major ice movement in South-East Scotland, (after Pringle, Clapperton etc.)



area but not altogether absent. Some tend to occur as individual features, usually near a valley bottom rather than in large belts. An example was noted about 2 km north-west of Kelso where a sinuous esker system was superimposed on a drumlin tail for some distance before winding across flatter ground in a series of high mounds and undulating ridge sections to fade out on reaching the Eden Water. In some parts of the basin however extensive belts of fluvioglacial moraines have been mapped, notably south of the Tweed in the Branxton area (J.B. Sissons, 1972, pers. commun.)

Most of the inter-drumlin depressions, notably on the Carrboniferous area, show evidence of some meltwater activity generally as deposition or a till-washing process and this is considered in detail in chapter two. Major meltwater channels do exist however and the Eden Water occupies one of these. This channel has its source in an area referred to as the Gordeon Platform (Pringle, 1948) lying to the north of Gordon village. This area shows evidence of considerable ice stagnation and is part of a large belt of low ground stretching to the north-east into the Blackadder Water. The channel occupied by the Eden Water has been cut through several metres of rock in some sections as well as across drumlinoid forms with apparent disregard to topographic trends. The channel appears to be superimposed from within the ice. A similar origin is envisaged for another major channel showing similar tendancies that runs south to the Tweed at Coldstream. This is the channel of the Leet Water. Another major meltwater feature has its origins in the lee of the Kelso lavas south-west of Hume village and this channel runs parallel to topographic trends for several kilometres before joining the Leet Water in its straight course to the Tweed. This channel is occupied today by the Lambden burn.

CHAPTER TWO

THE STRATIGRAPHY OF THE CONTINUOUS SECTION

INTRODUCTION

During late 1969 and early 1970 a natural gas pipeline was laid across part of the Tweed drumlin field, running generally at about 50 degrees to drumlin alignment although varying locally (Fig. 2). The trench excavated was over 2 metres in depth along most of its length and small sections locally reached down to 4 metres. (A depth of topsoil of 30-45 cm had already been removed prior to trenching.)

Permission was gained to examine the section provided by this trench and to carry out sampling and orientation studies on it. This chapter is an examination of the materials and the stratigraphy of this section. This is not quite complete however although omissions are very minor. Small sections were missed particularly when flooding or collapse made examination impossible or too dangerous. Such sections were never more than a few tens of metres at maximum. Even in these cases it was possible to make some examination of the materials taken out to form the trench although any stratigraphy had been destroyed.

It is also recognised that some of the evidence to be presented is to some degree incomplete in itself. It was not possible to follow up all aspects of work done on the trench section. An example of this was the distribution of sand and gravel complexes on the lee side of some ice-moulded features where it would have been desirable to know more about distribution and pattern. Having no surface topographic expression to act as guide, such an investigation would have involved a comprehensive programme of boring and trenching. This was not possible in the context of this thesis where a complex pattern of stone-counts already provided a time-consuming basis to the research programme.

THE TILL OF THE STUDY AREA

Considerable variability is evident, particularly a regional variation evolved largely in common with the geological divisions running across the area (Fig. 2). The petrological content of the till will not be discussed in this instance but will form the subject of later chapters. There are several other characteristics of the tills however which show change over the length of the pipeline section.

1. COLOUR

Colour varies considerably, largely in response to geological change. This is best illustrated by Table 1 (below) where certain samples of the series taken from the base of the trench have been classified according to the Munsell scheme.

TABLE 1

Sample No.	Map Reference	Classification (Munsell)
Carboniferous Bedrock Area		
1	NT 857413	10 YR 5/4 Brown
3	NT 850414	10 YR 5/6 Yellowish-brown
4	NT 846415	10 YR 6/4 Light yellowish-brown
6	NT 839419	10 YR 6/4 Light yellowish-brown
7	NT 833422	10 YR 6/4 Light yellowish-brown
12	NT 801423	10 YR 6/4 Light yellowish-brown
13	NT 796422	10 YR 6/4 Light yellowish-brown
15	NT 782421	10 YR 6/4 Light yellowish-brown
16	NT 777420	10 YR 6/4 Light yellowish-brown
22B	NT 757418	7.5 YR 5/4 Brown
23	NT 756419	7.5 YR 6/6 Reddish-yellow

Sample No.	Map Reference	Classification (Munsell)	
26	NT 743419	7.5 YR 5/4	Brown
Rd.X.12B	NT 736419	10 YR 6/3	Pale brown
29	NT 732420	7.5 YR 6/4	Light brown
30	NT 728422	5 YR 5/4	Reddish-brown
Basalt Bedrock Area			
31	NT 725423	7.5 YR 5/4	Brown
32	NT 719424	5 YR 5/4	Reddish-brown
32Y	NT 716425	5 YR 4/4	Reddish-brown
33	NT 716425	5 YR 4/4	Reddish-brown
34	NT 712426	5 YR 5/6	Yellowish-red
Old Red Sandstone Bedrock Area			
35C	NT 703428	2.5 YR	Red
38	NT 689429	2.5 YR	Red
40	NT 683429	2.5 YR	Reddish-brown
41	NT 678431	2.5 YR	Red
42	NT 675432	2.5 YR	Red
43C	NT 673434	2.5 YR	Red
X	NT 643446	5 YR	Yellowish-red
G.1	NT 638446	2.5 YR	Red
G.5	NT 627443	2.5 YR	Red
G.6	NT 621444	2.5 YR	Light reddish-brown

Some colour variation is also evident within the vertical extent of many sections, particularly where the base of the section lies close to bedrock. Examples of this are noted below (Table 2).

TABLE 2

Sample No.	Map Reference	Classification (Munsell)	
Carboniferous bedrock area			
TOP Rd.X.12A	NT 736419	7.5 YR 5/4	Brown
BASE Rd.X.12B	NT 736419	10 YR 6/3	Pale-brown
Basalt Bedrock Area			
TOP 32X	NT 718424	7.5 YR 5/4	Brown
BASE 32Y	NT 718424	5 YR 4/4	Reddish-brown

Sample No.		Map Reference	Classification (Munsell)
Old Red Sandstone Bedrock Area			
TOP	35B	NT 701428	7.5 YR 5/4 Brown
BASE	35C	NT 701428	2.5 YR 5/6 Red
TOP	43A	NT 673433	7.5 YR 5/4 Brown
MIDDLE	43B	NT 673433	5 YR 5/6 Yellowish-red
BASE	43C	NT 673433	2.5 YR 5/6 Red

These colour variations with vertical extent are partly explicable in terms of the differing origins of the materials at different levels in the sections. This idea will be discussed more fully in subsequent chapters.

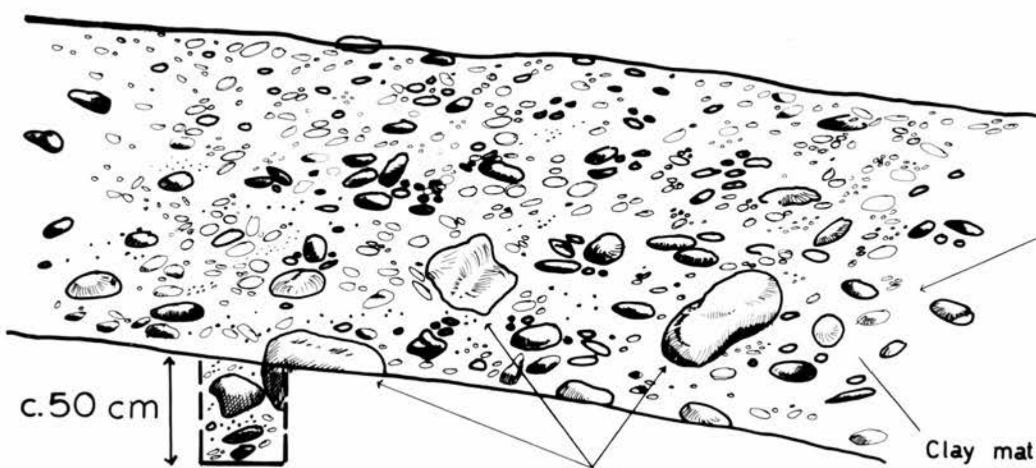
2. STONE CONTENT

As in any till derived from an ice sheet of potentially changing thickness and velocity and hence varying erosional activity, and moving over changing geology, it is not unreasonable to find areas within the tills of greater or lesser stone concentrations. Generally these till variations as they occur in the Tweed area cannot be attributed to any pattern. They do not, for example, appear to occur in any specific location in relation to drumlin form. Change can occur quickly over a few metres although it is generally true that a greater degree of homogeneity occurs farther east in the deeper tills of the Carboniferous area. Fig. 8 illustrates a typical till in this area. This relatively stoney till is dominated by well-rounded Silurian greywackes commonly 15 cm or more in their longest axis. Any boulders present are generally basaltic though these become less frequent eastwards.

There are four main instances in which below-average stone concentrations are found. These are as follows.

(a) Some areas occur, as already suggested, in apparently haphazard pattern. Many are even on the Carboniferous area and apparently

FIG. 8 A TYPICAL TILL OF THE CARBONIFEROUS AREA



SECTION APPROX. 2 metres deep. View is obliquely up-ice.

M.R. 853413

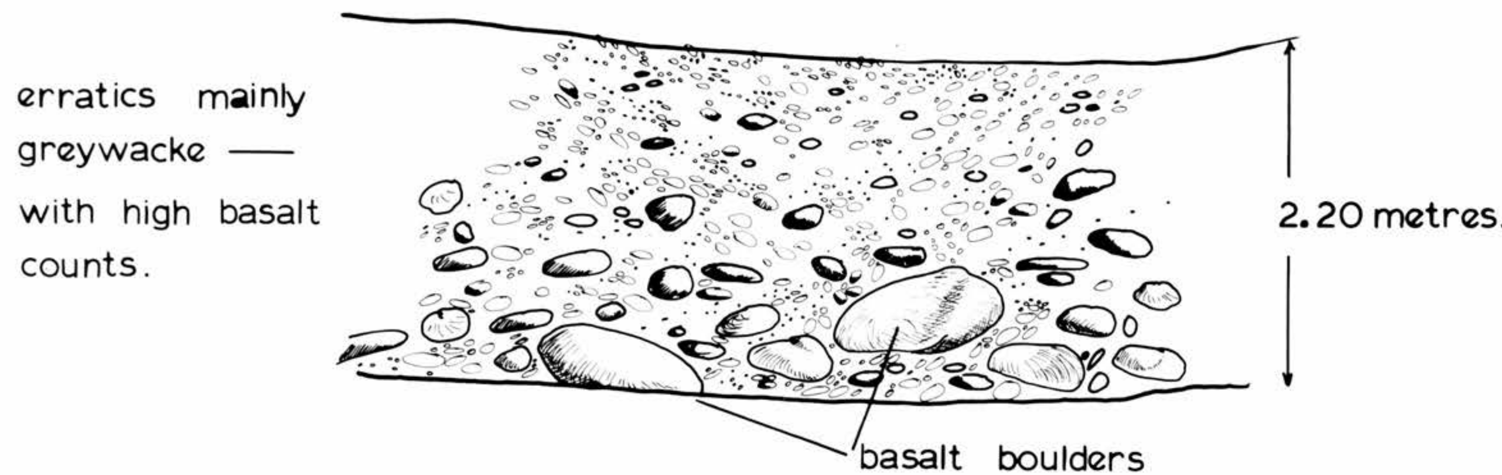
NT

reflect some variability in former glacial activity. Differences are often quite small and localised. (Some notably stone-free areas of a sandy nature are discussed later in this chapter.)

(b) A general tendancy is noted in many areas for tills to become apparently less stoney nearer the surface. This is not necessarily due to a fall in number of stones per unit volume but rather a fall in stone-size (Fig. 9). The upper horizons affected by agriculture could of course have had many larger stones physically removed or broken up but it is still apparent that the trend exists below the level of tillage. (Much of the topsoil had already been removed from the section prior to trenching.)

(c) In parts of the Old Red Sandstone Area in particular, some sections towards the base of the trench gave the appearance of being low in stone content. Closer inspection would reveal varying amounts of local sandstone in the process of breakdown. The susceptebility of the Old Red Sandstone to glacial erosion was very marked and tills on this area often approached 100% Old Red Sandstone counts for as much as 1 or 2 m above bedrock. (Silurian and occasional igneous erratics came in nearer the surface at such sites. Silurian erratics were often notably small in size, many being under 5 cm, contrasting with the size of similar stones found even towards the surface in the Carboniferous area.) Part of the breakdown of the Old Red Sandstones (both physical and chemical) appears to have been accomplished since glaciation and possibly in some cases by later periglacial activity. Many sandstone erratics are broken and rotted <u>in situ</u> and it was often impossible to pick out a piece of solid sandstone

FIG. 9 Till section (Carboniferous area) M.R. 769417



THE TILL AT THIS SITE SHOWS AN APPARENT FALL OFF IN STONE SIZE TOWARDS THE TOP OF THE SECTION. THIS WAS NOTED AT SEVERAL SITES BOTH WITHIN AND OUTWITH THE CARBONIFEROUS AREA. (REF. CHAPTER 2) from the basal mass. Close inspection however, clearly revealed that this material is a sandy till with sandstone blocks and fragments within it, the whole mass being very compact (Fig. 10).

(d) There also exist areas of slope-wash materials and therefore not tills as such but derived from them. These deposits, containing only small stones, occur locally in a few depressions e.g. reaching a depth of 70 cm in depressions in the lee of the lavas near Hume. Evidence of such deposits is less widespread than might be expected and only occasionally do they reach 30 cm in depth. In most areas they were absent from the sections examined.

Areas of stone content of above average fall into two main categories. These are as follows

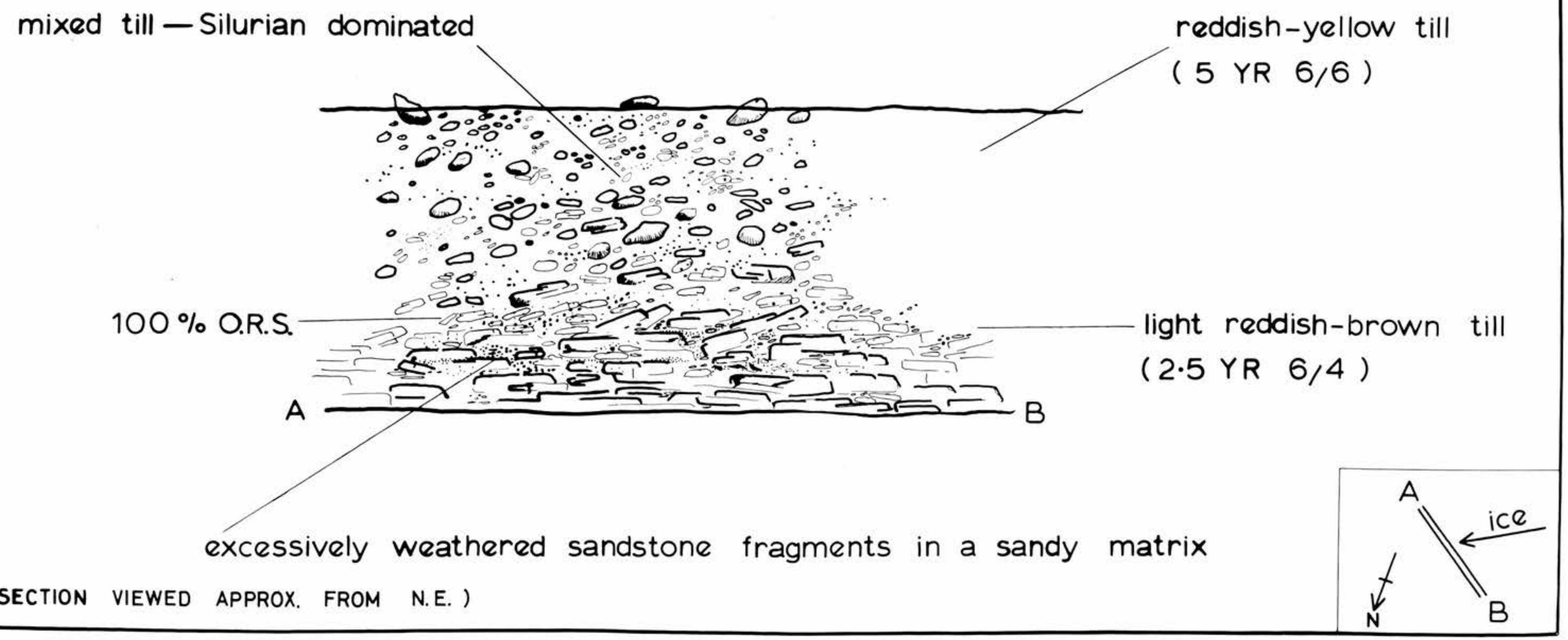
(a) There are areas which appear haphazard in their distribution and are not readily explicable other than by reference back to some aspect of the glacial environment. As with the more stone-free areas already referred to, these do not appear to follow any pattern such as in terms of position on drumlins.

(b) An area of particularly stoney tills occur on the basaltic lavas and immediately down-ice of this. Here the lower metre of the section is often in a till of almost 100% basalt fragments within a limited matrix (Fig. 17c). Fig. 11 shows a typical till just down-ice of the basalts, a till in which boulders are frequently found.

3. BOULDERS

The term "boulder" is applied in this instance when the longest axis is 30 cm or more. The pattern of boulder occurrence over the study area is worthy of some examination. The Old Red

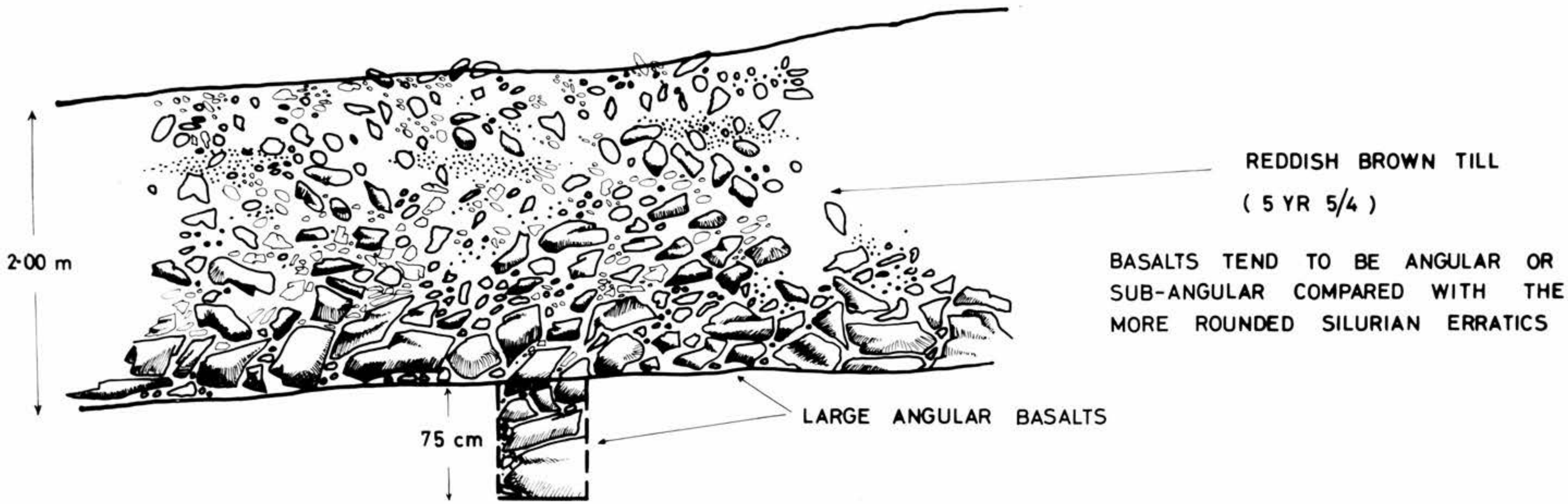
FIG. 10 Till section (Old Red S'stone area) M.R. 621447



(SECTION VIEWED APPROX. FROM N.E.)

FIG 11 Till section (Carboniferous - Basalt junction)

M.R. 725423



THIS SECTION SHOWS A TYPICAL STONEY TILL – AS WAS FOUND ON, OR JUST DOWN ICE OF, THE BASALT BEDROCK AREA.

Sandstone and Carboniferous sedimentary rocks do not appear to give rise to quantities of boulders, at least in the upper 2 m or so as exposed in this section. Locally these are seen however as in the Old Red Sandstone area near Gordon village (~~M.R.~~ NT 624447) where large stone-piles taken off fields contain sandstone blocks of over 40 cm. This is an area of often shallow tills.

Boulders of Carboniferous sandstone were similarly only found closer to bedrock. The only examples noted were on the ridge of green micaceous sandstone east of Hume village (~~M.R.~~ NT 732420) where sizeable slabs of sandstone had been picked up into the till (Fig. 17a). In the flanks of the meltwater channel now occupied by the Lambden burn immediately north-west of this site, a block of sandstone some 2.5 x 1.5 x 1 metres was seen to have been broken off and incorporated some 25 cm into a sandy matrix above solid bedrock. The life of such sandstone fragments once in the transportational environment of the ice seems to have been short however.

Silurian rocks did not generally give rise to large boulders in the tills of the study area and only in the west of the Old Red Sandstone area were Silurian erratics of boulder dimensions to be found. These Silurian examples were all found in stone piles gathered off the fields and none in the till sections examined.

Basalts account for the main boulder content of the tills with an appreciably high density of boulders noted at many locations in the upper two metres. These arise both from the Kelso Lavas and from the various basic intrusions described in chapter two. (The fewer acid intrusions do not appear to have given rise to boulders to the same extent. Later studies on

Black Hill near Earlston tended to support this view.)

Some major basalt boulder concentrations occur within about 2 km of the basalt outcrop although specimens are found at much greater distances from source. There did appear to be evidence of particular concentrations on the stoss ends of certain drumlins but this evidence as provided by the section was so limited as to make further study desirable before drawing any definite conclusions.

4. THE FINE CONTENT OF THE TILLS

Variability can be recognised within the matrix or finer fraction of the till even within the relatively homogeneous bedrock of the Carboniferous area. Much of this variation appears to be largely a response to changing bedrock type. Many sandy areas of till appear to occur very locally in response to underlying sandstones of Upper Old Red or Lower Carboniferous age. This will be shown particularly clearly in the Old Red Sandstone area on the tail of Knock Hill near Gordon and on Greenlaw Moor. Alternatively, underlying shales and marls tend to produce a finer-textured till with more material in the silt and clay grades.

Silurian influence on the matrix might enhance the sand and silt fractions through the greywackes or the clay fraction through the finer shales (Ragg et al., 1960). The net result is a medium textured till which Ragg et al. considered to be mainly confined to the Silurian bedrock area. Silurian influence is much more widespread than this however, both in the finer fractions and in the stone-counts. Although for the most part the matrix of tills on the Old Red Sandstone area seems to be largely a response to local bedrock there are notable exceptions, particularly where tills are deeper. The Carboniferous till area potentially gains its character from the effects of all geological groupings, especially in the deeper tills where local influences are less. To examine such questions particle size analyses were carried out on selected samples. (Heavy mineral analyses also contribute to this investigation and are discussed in a subsequent chapter.)

PARTICLE SIZE ANALYSIS

During field studies samples were taken at intervals from the base of the trench. These are referred to as the "basal series" of till samples. (Stone-counts from this series are discussed in detail in chapter three.) Particle size analyses were also carried out on a number of samples taken at different levels in the trench. Overall some 48 samples from the trench were analysed, using the hydrometer method (Fig. 12). This method is outlined in chapter six.

Fig. 13a shows all the particle size analyses of the basal series. Patterns are evident which distinguish different till "types" particularly in response to local geology. Certain apparent anomalies do exist however. For example, in sample Rd X 12B, taken from a till of near 100% Carboniferous sandstone content, particle size analyses give results more typical of tills of the Old Red Sandstone bedrock area. Over the rest of the Carboniferous area examined, tills are much deeper and hence further removed from potential local bedrock influences. This is reflected in the particle size patterns which emerge. Fig. 13b shows these patterns in more detail. They are best studied with reference to geological area.

TILLS OF THE OLD RED SANDSTONE AREA

Tills in this area were dominated by high percentages in the sand

FIG. 12.

LOCATIONS OF THE 48 TRENCH-LINE SAMPLES EXAMINED IN PARTICLE-SIZE ANALYSES.

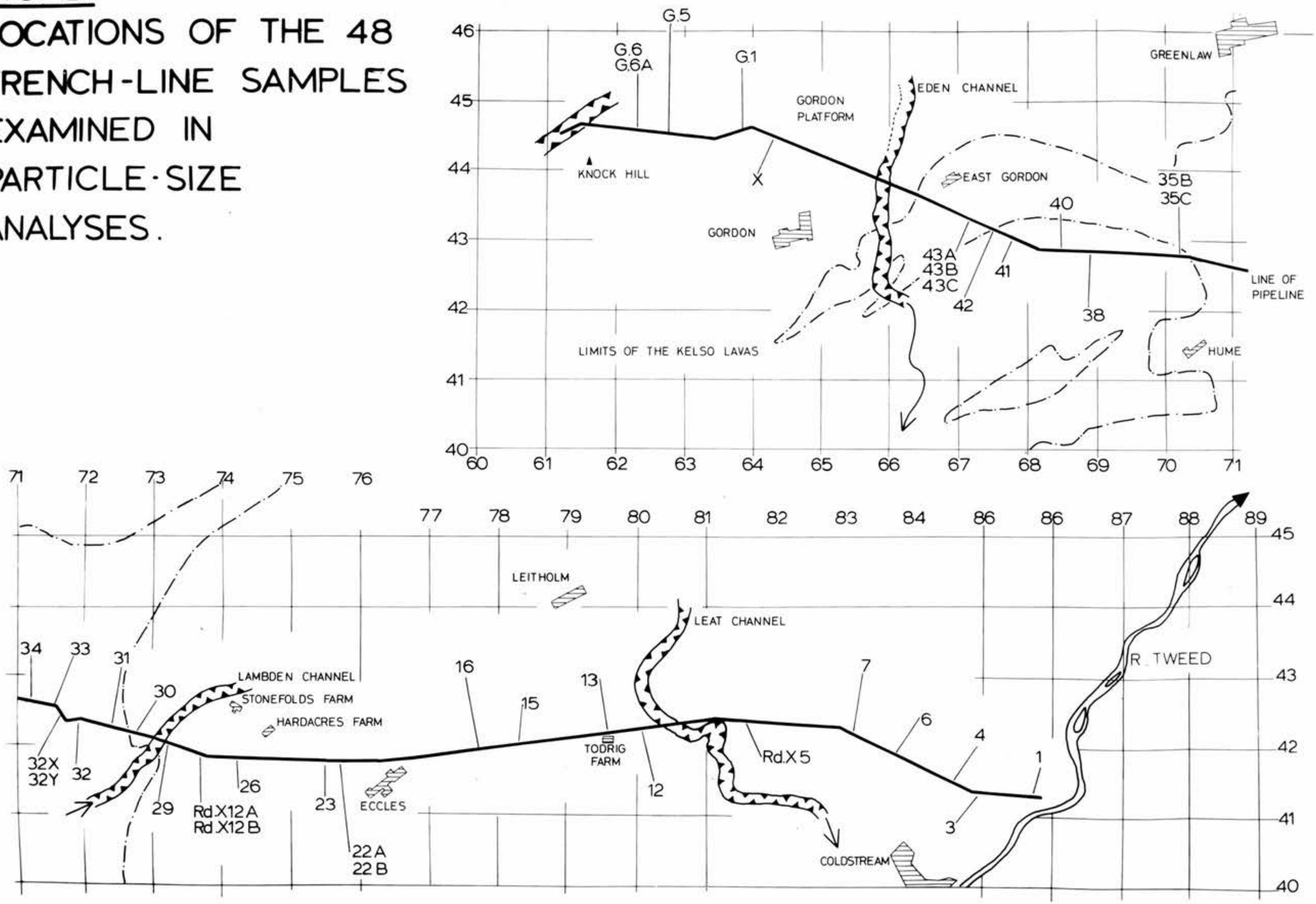


FIG. 13a.

PARTICLE SIZE ANALYSES OF SOME SAMPLES FROM THE BASAL SERIES.

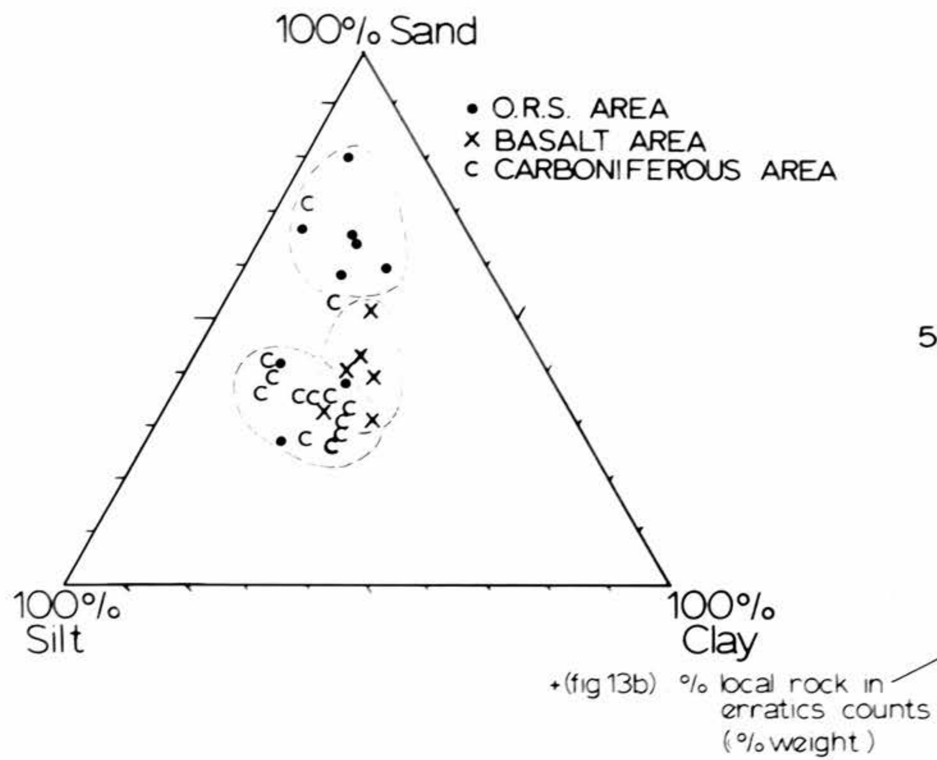
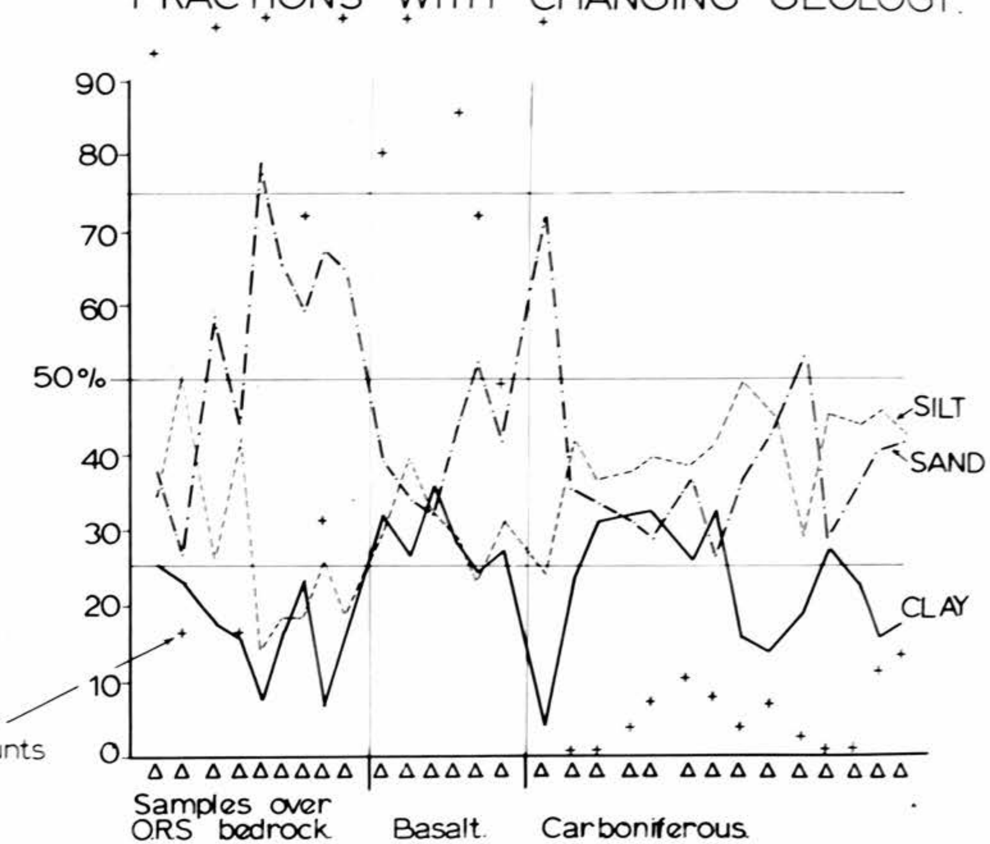


FIG. 13b.

VARIATIONS IN SAND, SILT & CLAY FRACTIONS WITH CHANGING GEOLOGY.



fraction and most samples were particularly high in the fine-sand fractions (Fig. 13c). Only three out of nine samples had sand fractions of less than 50%-samples SX, S.G.5 and S.G.6.

Two of these samples (G.5 and G.6) lie well to the west (i.e. up-ice side) of the Old Red Sandstone bedrock area and yet sample S.G.6 in particular lies very close to Old Red bedrock. The fraction however would appear to derive more from Silurian and perhaps basaltic influences, although also potentially from finer-grained Old Red Sandstone rocks. It will be suggested subsequently that the high silt percentages are often indicative of Silurian influences. (S.G.5 had a Silurian stone-count of 57%.)

The third sample, S.X., lay in an area of deeper till on part of the Gordon Platform (~~M.R.~~ NT 644445) where the evidence from stone-counts and colouring endorsed this idea of greater Silurian influence. Typically, the silt fraction is high in S.X. as a result of this influence.

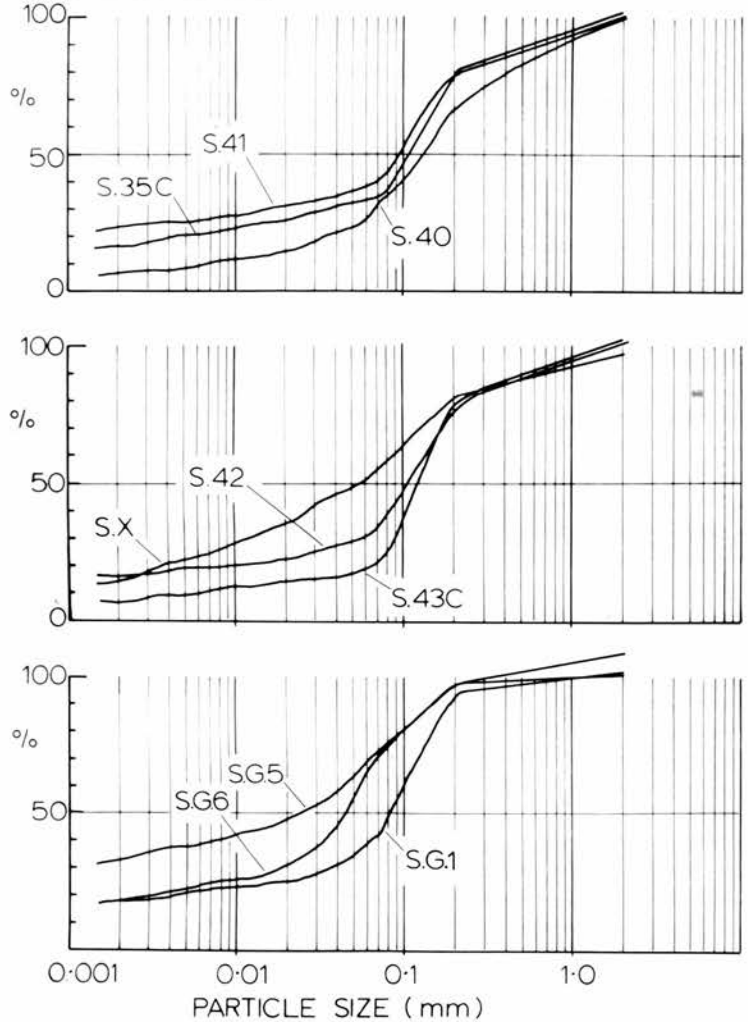
Otherwise, on moving eastwards (i.e. down-ice) in the Old Red Sandstone bedrock area the sand fraction (with most in the fine-sand sector - Fig. 13c) remained constantly 60% or more in the other six samples examined, even where stone-counts of Old Red Sandstone fell to 31% as in sample S.40. It seems that by this stage Old Red Sandstone influences were fairly apparent throughout the finer fraction of the tills.

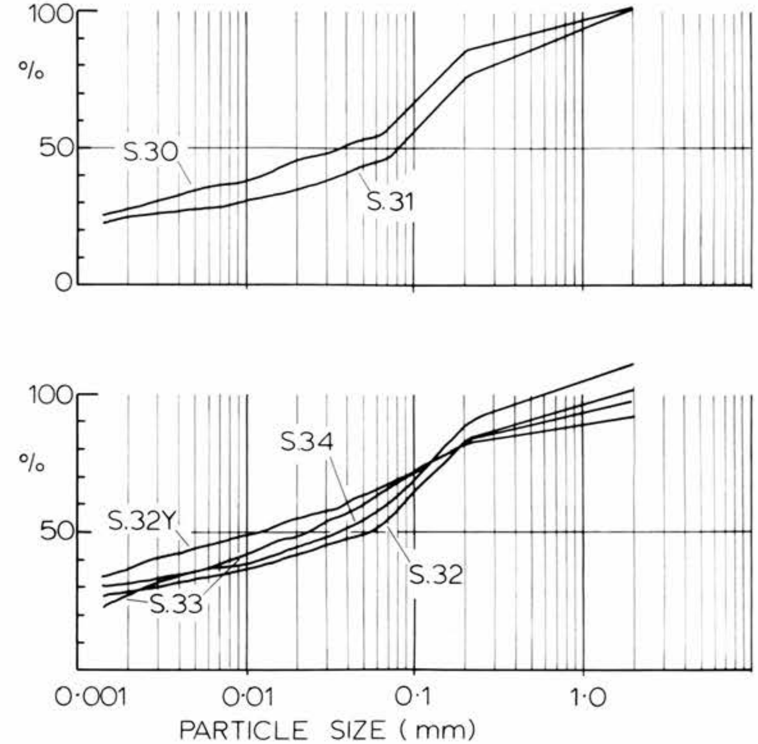
Tills of the basalt bedrock area

On the highest parts of the basalt ridge where basalt stone-count percentages were high in samples of the basal series, (chapter three) there was a sudden and marked fall in the sand fraction percentages and an equally marked rise in both clay and silt content. This reached a maximum in samples S.33 and S.34 on the crest of the basalt ridge (Figs. 13b and 13d). Eastwards (down-ice) onto the tail

PARTICLE SIZE ANALYSIS OF BASAL TILLS.

FIG.13c. OLD RED SANDSTONE AREA. **FIG.13d.** BASALT AREA





VERTICAL AXES : CUMULATIVE %

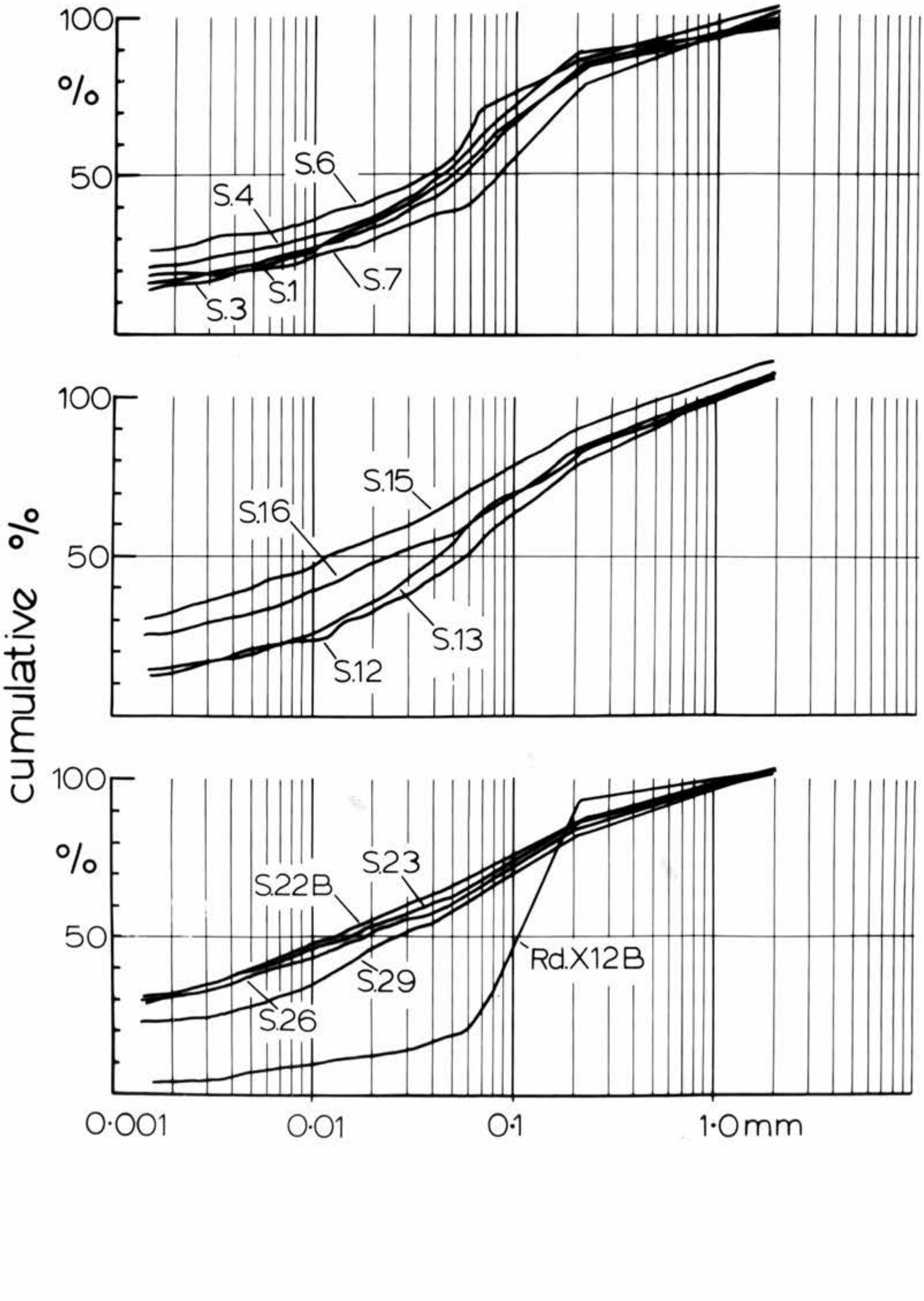
of the lava outcrop, basalt influences declined slightly in the greater depths of till overlying local bedrock and samples 32 to 30 saw a slight increase in the sand fractions at the expense of both silt and clay fractions. Possible explanations for this were suggested in the increasing numbers of Old Red Sandstone erratics in the stone-counts (chapter three). From stone-counts of well under 5% Old Red in samples on top of the ridge, these rose to 16% and 18% in S.32 and S.30 respectively. Counts of a finer size of 'pebbles', (chapter five) showing 22% Old Red in S.32 and 13% (from 4% in the stone-count) in S.31 further endorse the view that Old Red Sandstone influence is carried over into the Carboniferous area, particularly in the finer particles.

Tills of the Carboniferous bedrock area

Basal tills examined on the Carboniferous area had generally large silt fractions (nearly 50% in sample S.15) with sand percentages of generally 40% or less. Clay percentages varied between 15% and 30% with highest values tending to occur towards the west of the area studied (Figs. 13b and 13c). The major exception to this relative homogeneity lay in sample Rd.X 12B where the clay fraction fell to under 5% and the silt fraction to under 25%. The very high sand percentage is due to this being the only sample examined which lay close to Carboniferous bedrock. (The stone-count was 100% Carboniferous.)

Elsewhere in the Carboniferous bedrock area local bedrock influences on till composition appear weak and counts of Carboniferous erratics support this idea. The high silt percentages may be derived in part from the basalt area but in the light of the very limited extent of the basalts in the down-ice direction and the evidence discussed from the Old Red Sandstone area it is suggested that the most likely source lies in the considerable Silurian influence in the tills

FIG. 13e Particle size analyses of tills overlying Carboniferous bedrock.



of this area. This will be supported by evidence presented in later chapters. Likewise therefore much of the clay fraction might also derive from the Silurian region though it will subsequently be suggested that basalt influence is perhaps important. Conclusions on the derivation of this finer fraction of the tills cannot come from particle size analysis alone however.

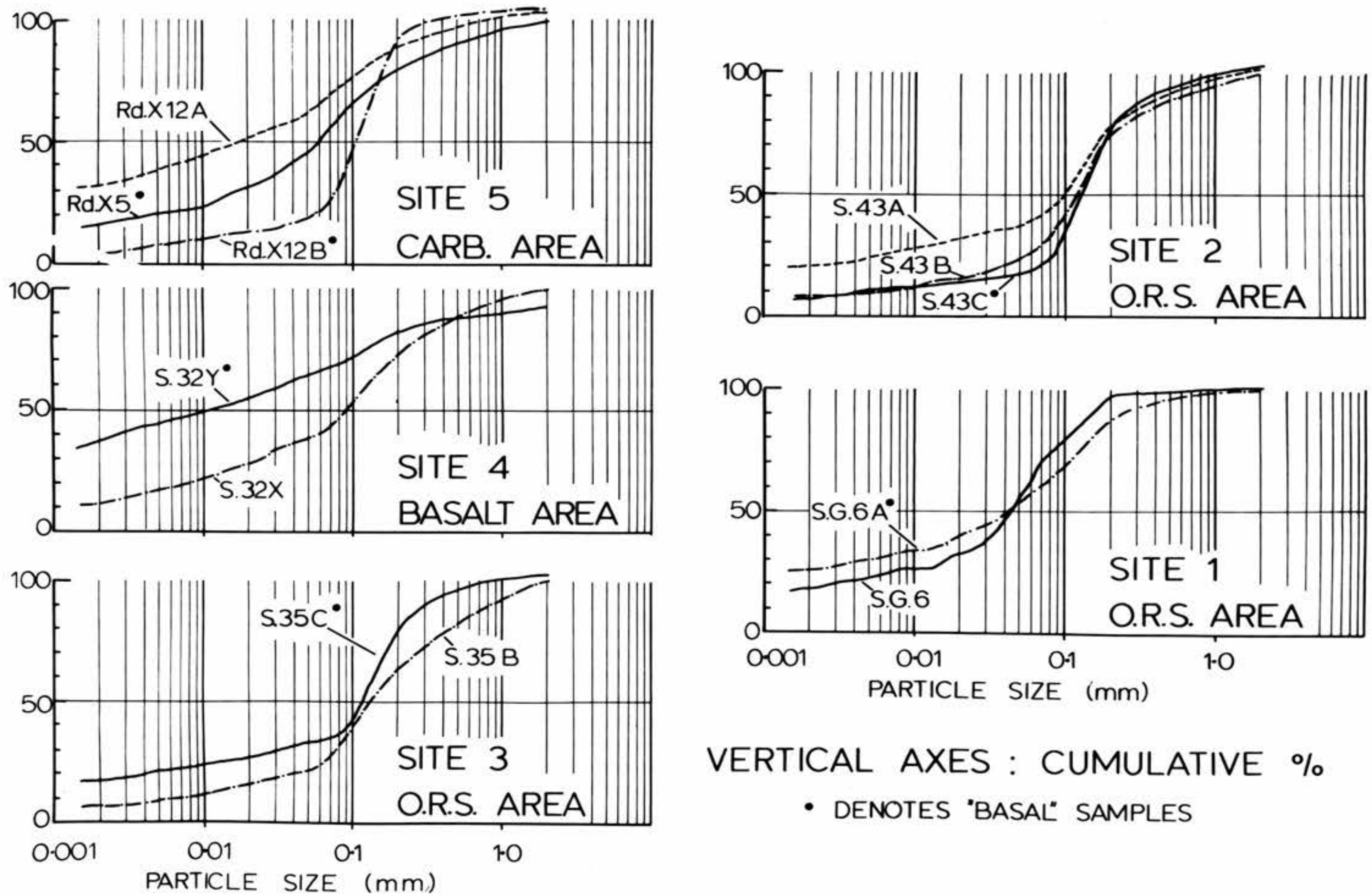
Studies from different levels in the section

Apart from the study of the basal till series, analyses were also carried out at different levels within the trench section. The samples examined in this instance are not an attempt to distinguish between true "basal" and "melt-out" tills associated with the undermelt ideas expressed later in this chapter. This is not to say that melt-out tills could not have existed in some of the sections considered here. However no specific evidence of melt-out existed in this instance. In most sections, especially outside the Carboniferous bedrock area there often existed a general change from top to bottom of the section. This was perhaps most notable in colour but also in stone-content and, as will subsequently be shown in origins of material. In the sections examined here however there was no evidence to suggest that this was anything but one till unit.

Five sites were examined; three in the Old Red bedrock area and one each in the basalt and Carboniferous bedrock areas. Results are shown in Fig. 13f.

Site 1 lies well to the west in the Old Red Sandstone area on the tail of Knock Hill, a basaltic plug near Gordon village (~~N.R.~~ NT 624447). In this a sample from the basal series (S.G. 6A) and one taken within one metre of the surface (S.G.6), were examined. Later stone-count evidence showed high percentages of Old Red Sandstone in the base but these fell off very quickly to only 6% in sample S.G.6. Particle

FIG. 13f. PARTICLE SIZE ANALYSIS OF TILLS FROM DIFFERENT LEVELS IN THE TRENCH SECTION.



VERTICAL AXES : CUMULATIVE %

• DENOTES "BASAL" SAMPLES

size analysis provided results which in many ways were unexpected, notably the relatively low sand fraction (38.5%) in a basal sample apparently dominated by a fairly course sandstone rock. A silt fraction of 36% and more particularly a clay fraction of 25.5% are perhaps unusual in this situation. Apart from the possible occurence locally up-ice of finer Old Red Sandstone rocks the origins of this material are difficult to explain. While Silurian and some basalt influences are possible it is difficult to argue this in view of the lack of erratics of easily handled macroscopic size. The origins of the surface till are more readily apparent, the high silt fraction being seen as indicative of Silurian rocks, particularly greywackes.

Site 2 lies farther east in the Old Red Sandstone area on the lee slope of the East Gordon ridge (Fig. 32) and Old Red Sandstone floors the trench at this point (M.R. NT 673433). Here, three samples were taken at basal, intermediate and near-surface levels; samples S.43C, 43B and 43A respectively. (Stone-count results from these samples are indicated in Fig. 32.) Particle size analyses gave high sand fractions in all three samples suggesting a much greater Old Red Sandstone influence in the "fines" content of these tills than was noted in the surface till at site 1. (Sand percentage was 57% in S.43A with the bulk of this again in the fine sand range.) Clay percentages increased towards the surface i.e. away from bedrock reaching a maximum of 20% in 43A. Silt percentages are generally similar at about 23% in the upper two samples but are less in the basal sample. (Silurian stone-counts are approximately similar in the upper samples (43% and 47%) but are nil in the basal sample.)

Site 3 lies even farther to the east in the Old Red Sandstone area (M.R. NT 701428). Sample S.35C is a basal sample and S.35B is a near-surface sample. The results of analysis in this case appear at first to contradict the general pattern which has been emerging in that the sand percentage in this case is highest in the surface sample and the clay fraction greatest in the basal sample. The result however is not anomalous. The maximum clay percentage, although in the basal sample, is low (16%) and as such, perhaps readily explicable in terms of Old Red Sandstone origins. The fall in clay percentage in the "surface" sample may be due either to derivation of tills at that level from courser parent material, or to some squeezing or washing of till during deposition, in the manner envisaged by Carruthers (1939). The basin has extensive evidence of melt-out and the presence of abundant water during the final stages of deposition. (This is discussed fully in the next section of this chapter.) The higher sand percentage in the surface count is minimal (only 6% difference) and, more significantly both sand counts are high suggesting strong Old Red Sandstone influence at all levels in the till.

Collectively therefore, results of the Old Red Sandstone area suggest tills becoming increasingly high in sand content at all levels towards the east of the Old Red Sandstone study area. Farther west Silurian influences are stronger, especially where tills are deeper and thus farther removed from local bedrock. This influence is particularly reflected in high silt percentages, e.g. sample S.X. in Fig 13b.

Site 4 lies on the basalt bedrock area towards the lee slope of the main basalt body. Silt percentages between S.32 X (the near-surface sample) and S.32 Y (the basal sample) are not greatly different although the origins of the respective silt fractions need not necessarily be similar. The clay and sand fractions are more revealing. The high clay count (37%) in the basal sample is apparently directly related to the local rock (as also is much of the silt count in this instance). The surface clay figure would thus appear less typically basaltic (11%) and coupled with the higher silt (33.5%) and sand (55%) fractions points to Silurian and more particularly Old Red Sandstone influences being carried over at these higher levels.

Site 5, on the Carboniferous bedrock area, lies on the ridge of green micaceous sandstone south-east of Hume village (~~N.R.~~. NT 736419) and the section lay on bedrock. This latter fact is readily apparent in the high sand fraction of the basal sample, Rd.X 12B (72%). In the surface sample (Rd.X 12A) both silt and clay fractions increase markedly, from 24% to 39% in the silt count and from 4% to 32% in the clay count. The high silt percentage is again taken to indicate Silurian influence although some basalt influence must also be considered at this site. The markedly high clay fraction is less typical of Silurian influences as evidenced to date although Ragg et al. (1960) have recognised finer grained Silurian tills developed on the finer Silurian rocks. Evidence from site 4 however would suggest that at this site such a high clay count is more symptomatic of basalt influences. It was evident from samples of the basal series (Fig. 13b) that clay counts tended to be greater immediately down-ice of the basalt region where later stone-count results showed greatest concentrations of basalt erratics.

5. SANDS AND GRAVELS

Surface forms such as kames and eskers do occur within the study area but it is not intended to discuss these in detail in this instance. In only one part of the pipeline section were surface fluvioglacial deposits exposed. These were kames and eskers on part of the Gordon Platform. No till was exposed in the immediate area, and the relationship between kame or esker and underlying till was not evident. The consideration below is mainly of fluvioglacial materials noted in the section, generally in much more intimate relationship with the general till deposits. These will be shown to contribute to an understanding of the till itself. Sands and gravels in the section occurred in a variety of forms and differing conditions can often be suggested for their origins.

1. Surface deposits. This first group occurs in many of the inter-drumlin depressions, notably the major depressions at lower levels, many of which appear to have been extensively used by meltwaters. The deposits are found at or near the surface except in a few instances where they are masked by colluvium or later alluvium. Generally the materials are coarse-textured, often being composed of gravels of 15 cm and more in size and showing no apparent bedding. Sands and finer, bedded, gravels also occur. These deposits are most abundant in the Carboniferous area but were also recorded in the Old Red Sandstone area. They were not found on the basalt area crossed by the trench.

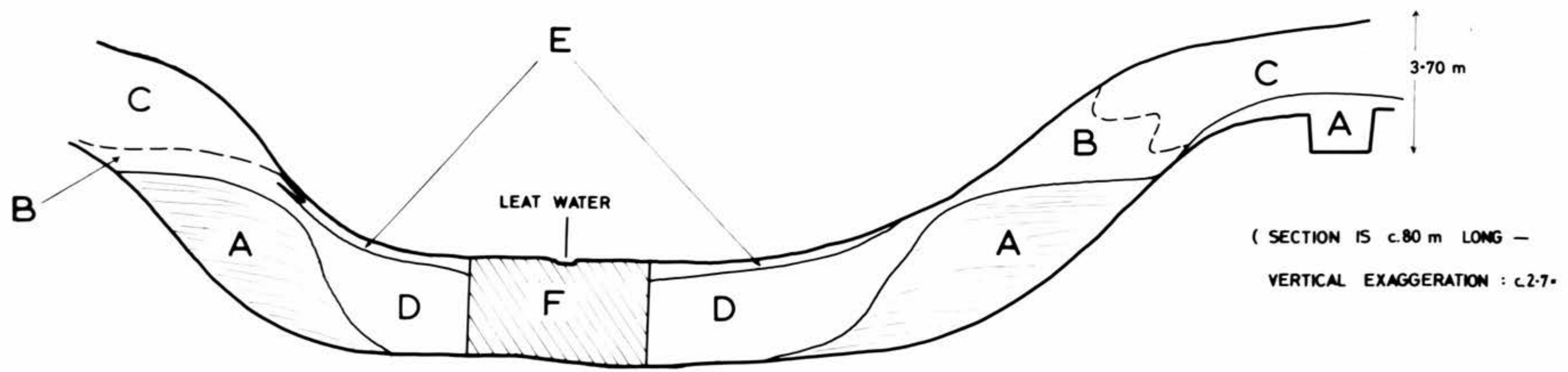
The deposits are seen as being derived from meltwaters flowing from stagnant ice, these waters flowing freely under gravity or at most flowing in contact with stagnant ice walls during the final stages of ice decay. The presence of some control in this way is suggested by examples noted elsewhere in the Carboniferous area (Ragg et al., 1960). A considerable flow of meltwaters is suggested both by the abundance and the coarseness of the materials described, notably in the Carboniferous area. In the Old Red Sandstone area for example there is evidence in the area of the Gordon Platform (Fig. 2) of the melting in situ of a considerable mass of stagnant ice. As will be shown later in this chapter there is also evidence for stagnation of ice over a much wider area. The deposits described above would be derived both direct from the debris within these stagnant ice bodies and also from the washing of tills by the abundant meltwaters. As well as the inter-drumlin depressions, the former sub-glacial meltwater channels were also utilised by these later meltwaters and the two examples exposed by the trench are illustrated in Figs. 14a and 14b. The channel now occupied by the Lambden Burn for instance shows a deposit of soliflucted till or flowtill on top of these gravels.

2. Sub-surface complexes. A second distinct group is recognised in the occurrence of bedded sands or complex layers of sand, grits and gravels. (The term "grit" is used to define material which falls in the size range between sand and what might be classified as fine gravels, i.e. approximately 2 mm to 50 mm equivalent spherical diameter.) These are usually found beneath the surface and beneath a till layer although occasionally they may approach the surface. Two types were recognised within this group as it was represented in the trench section although these are merely seen as variations on the same theme.

The first type was in the occurrence of clearly defined and preserved sand lenses or layers. These were of variable thickness and often clearly showed a pattern of current bedding. Occasional small lenses of grit only a few cm in length were noted in the sand in some instances but these were less common in this type of sand occurrence. The sand lenses and sand layers made up of connected lenses had well defined upper and lower limits. Such features were seen mainly in the complex tail of Knock Hill near Gordon village in the Old Red Sandstone area (Fig. 15d). As well as lenses of several metres in length (i.e. measured across ice direction, along the trench line) and approaching 1 metre in thickness, there were also some very small lenses of sand and occasionally of grits. These were found within the till usually above the major lenses and were also clearly defined in most instances. Lenses were not found on the steeper northern flank of the tail where it is bounded by a steep-sided meltwater channel and where ice erosion

FIG. 14 (a) SECTION ACROSS LEAT MELTWATER CHANNEL

M.R. 803424



A Excessively weathered/rotted bedrock – shales. (Lines indicate bedding.) Rock soft and friable up to 2 m down.

B Sands and gravels – no apparent bedding. Some large stones (up to 30 cm). A stone-count of 100 samples in the gravels gave 48% Carboniferous, 31% Silurian, 15% Basalt and 6% others.

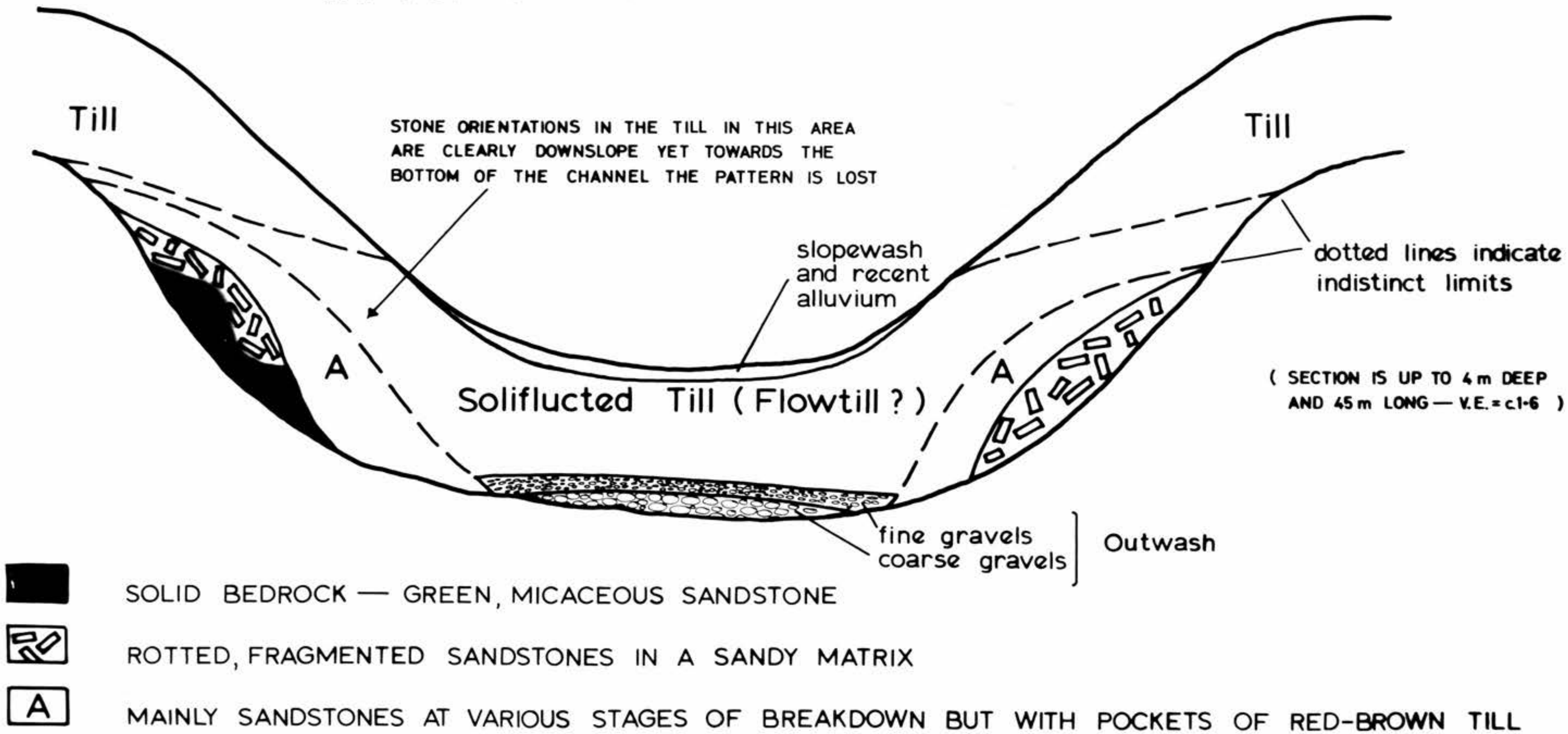
C Finer sands with a few small stones. Faint suggestion of bedding in parts. Merges laterally into till.

D Thick coarse gravels with some inter-bedded sands. (Outwash)

E Slopewash and recent alluvium.

F This area could not be studied because of collapse and flooding.

FIG. 14(b) SECTION ACROSS LAMBDEN BURN MELTWATER CHANNEL
M.R. 731421



appears to have been very active.

The second type of occurrence which could be recognised was in the form of alternating and often quite thin (under 10 cm) layers of sands, grits and gravels. The latter were generally fine. Bedding was often contorted, faulted and discontinuous and tended to merge fairly gradually laterally into till or general sandy or gravelly areas with no apparent bedding. Upper boundaries varied from sharp features to indistinct mergers due to incorporation of patches of till into the deposits. It was not always possible to examine the base of these deposits although where this was possible the boundary with the basal till was a distinct one. (Figs. 15b and 15c.)

Although different to some degree in their end products the two types are seen as being produced by similar environments. This is envisaged as being under stagnant ice with a heavy debris load in its basal layers. This ice is considered to have melted slowly <u>in situ</u>, depositing till in intimate relationship with greater or lesser amounts of water-sorted material during melt-out.

The idea of basal melt-out is not new. As long ago as 1875, J.C. Goodchild held that drifts in his northern Pennine area were of englacial origins. He recognised a bottom-melt leaving behind till and gravel. Such ideas were much elaborated by Carruthers (1939) in his discussion of an undermelt drift sequence in glacial drifts. Carruthers identified as distinctive of the undermelt process, a sequence of deposits that he suggested had been laid down in the reverse order of what might be expected from normal top-melt. While some of Carruther's ideas on the processes involved may be seen to be relevant to the Tweed situation, the overall pattern he describes is less evident. There is, for example, no sign of any survival of laminated clays in the area studied and the undermelt process is restricted largely to the upper few metres of the till.

More recently workers such as Boulton (1970) and Shaw (1971) have referred to the importance of basal melt-out. Boulton described a basal till, referred to as a melt-out till, released by the melting of masses of buried, debris-rich stagnant ice. In the glaciers of Spitzbergen today, tills that are being produced by melt-out are retaining some of their englacial fabrics. Some fabrics however may be changed in the melting out process, usually through movement caused by subsequent melt-out of buried ice blocks or removal of supporting ice-walls. Shaw noted a final undermelt process operative in a complicated drift sequence associated with the "Little Welsh Advance" near Shrewsbury. He identified this process by such features as the collapse of small ice blocks within the deposits and pointed to this release of an upper till by undermelt. However, Shaw considered the very final stages of melt-out to be top-melt.

There is a tendency towards a prevalence of lee sites in these sub-surface fluvioglacial sequences within the study area. It is perhaps dangerous to attach significance to this point considering the relatively limited nature of the sections studied, but the possibility exists of some cavity development in the lee of these larger bodies which might have assisted the formation of these fluvioglacial arteries. Equally these cavities, and the waters which utilised them, might have had their origins in the time before final ice stagnation. Pressure melting on the stoss sides of these larger bodies, for example, could have supplied waters which as conditions ameliorated, might not have been re-frozen immediately in lee localities. The two major sub-surface complexes noted were (a) on the very wide tail of Knock Hill, a basaltic plug in the Old Red Sandstone area and (b) in the lee of a particularly imposing drumlinoid feature with a double tail located near Eccles village in the Carboniferous area. (Some degree of bedrock control was suggested in the latter feature.)

G. Boulton (1973, Lecture) showed positive existance of cavity development down to a very small scale in observations in the glacier d' Argentieres in the Alps. (3 cm clasts dragged over the glacier bed.) Cavities in this instance were caused by the frictional drag of the particles on the glacier bed, the larger particles apparently being retarded most and therefore being even more susceptible to cavity development. Boulton also pointed to the existance of a thin water layer between the body and the glacier sole, This has been suggested previously by many workers. As faster particles tended to catch up with slower moving particles in the glacier sole so debris/ice concentrations of over 50% were noted.

While the possible contributions of cavity development is recognised it is not absolutely necessary to the development of the fluvioglacial sequences referred to. Gradual concentration of the melt-waters produced by squeeze-melt into several major arteries of movement was recognised by Carruthers for example. These are evident in the sections examined as the extensive fluvioglacial complexes. Under conditions of abundant water supply there is the possibility of some lens development under moving ice and thus the incorporation of sand lenses within true lodgement till. However, the large complexes described here, particularly in the forms in which they survive in the section, could only be formed under stagnant ice. This will become especially evident as certain sites are examined in detail.

Sands and gravels from the melting basal ice would develop both on top of the underlying lodgement till and also laterally within the heavily laden basal ice. During this process there would be frequent mixing with the till held in the ice with roof falls and till melt-out. Fragments of ice might be incorporated into the new deposits and this

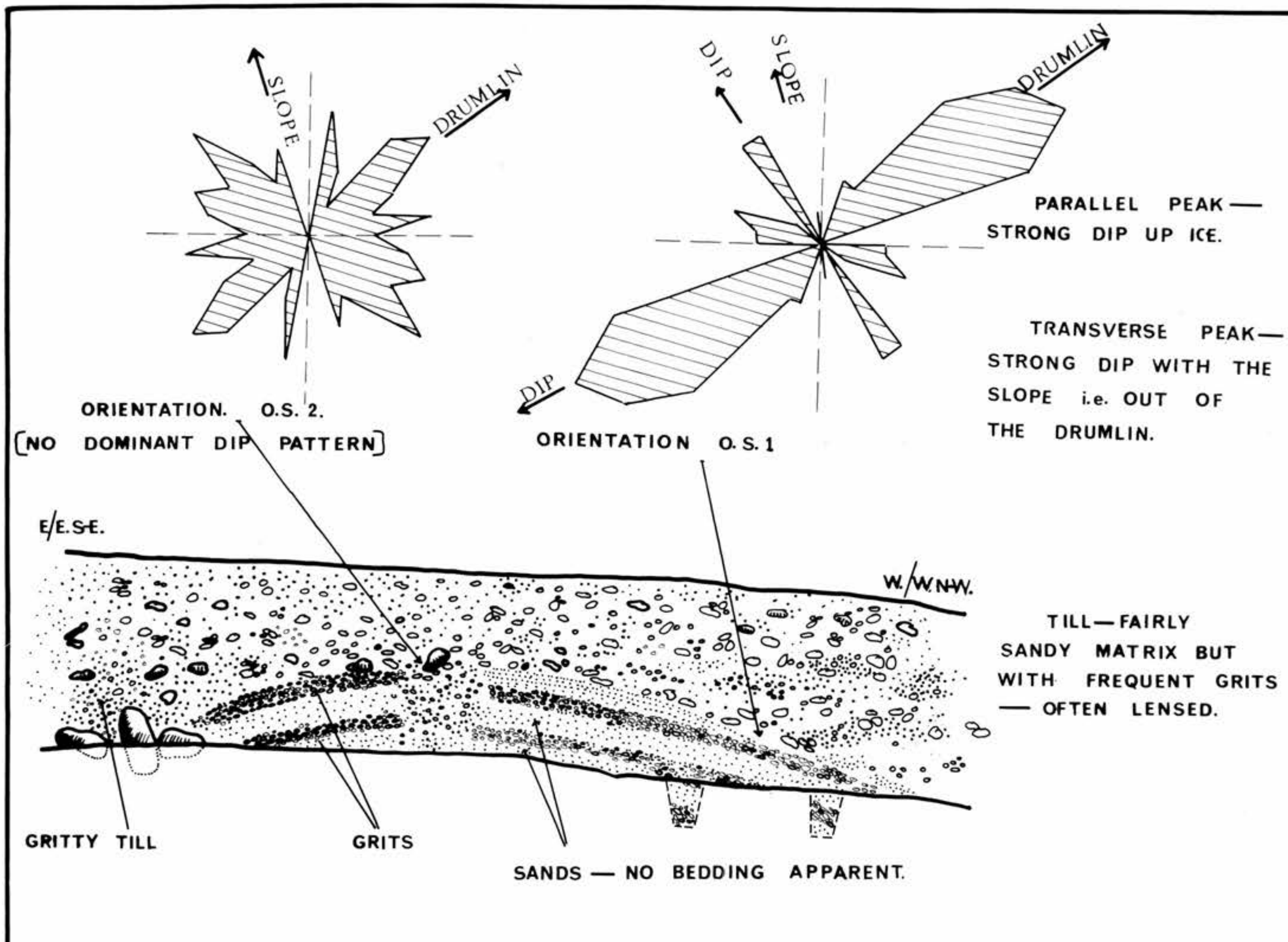


FIG. 15(A) M.R. 760417 (CARBONIFEROUS AREA)

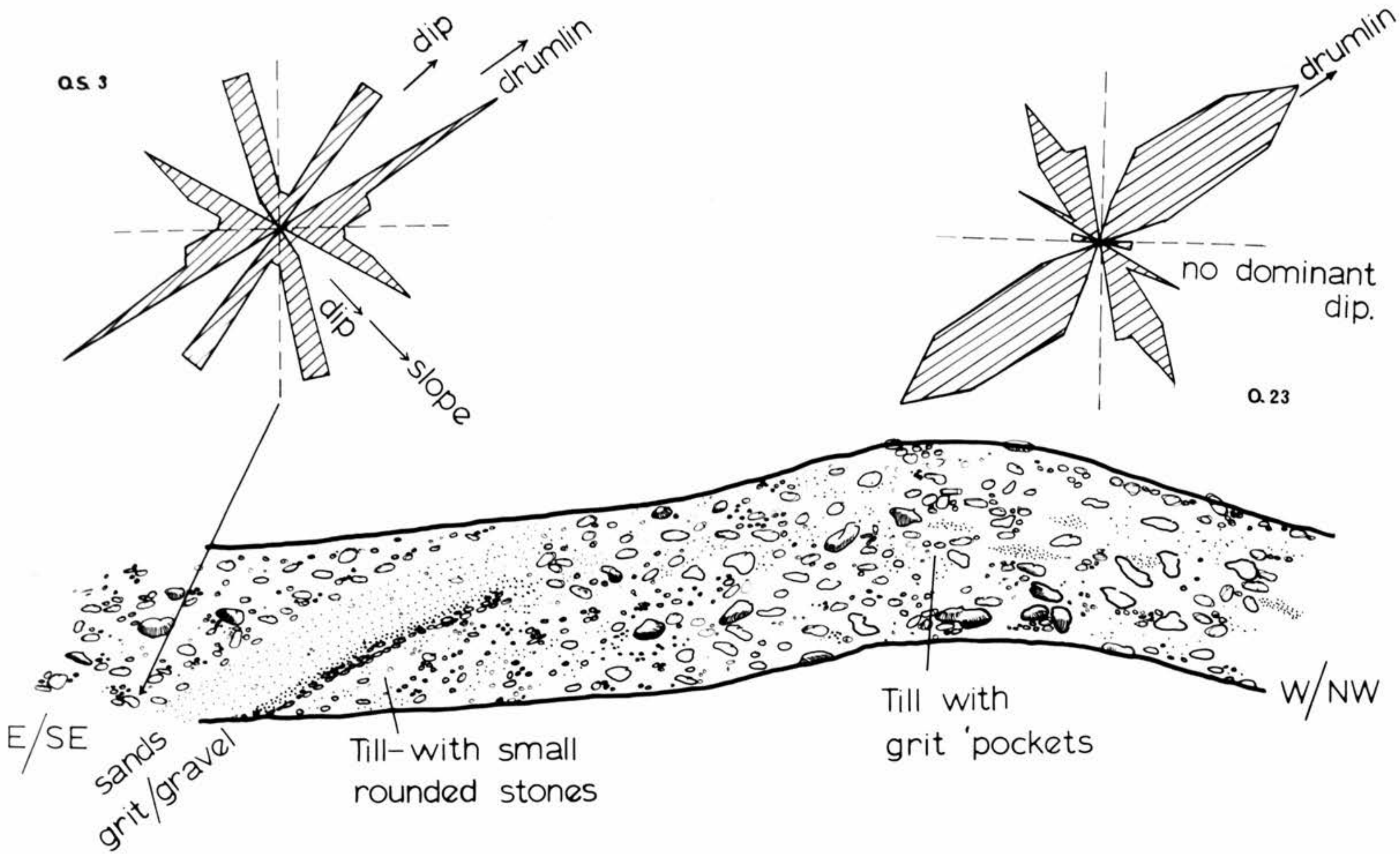


FIG 15(B) M.R. 761417 Section lies immediately east of Fig. 15 (A)

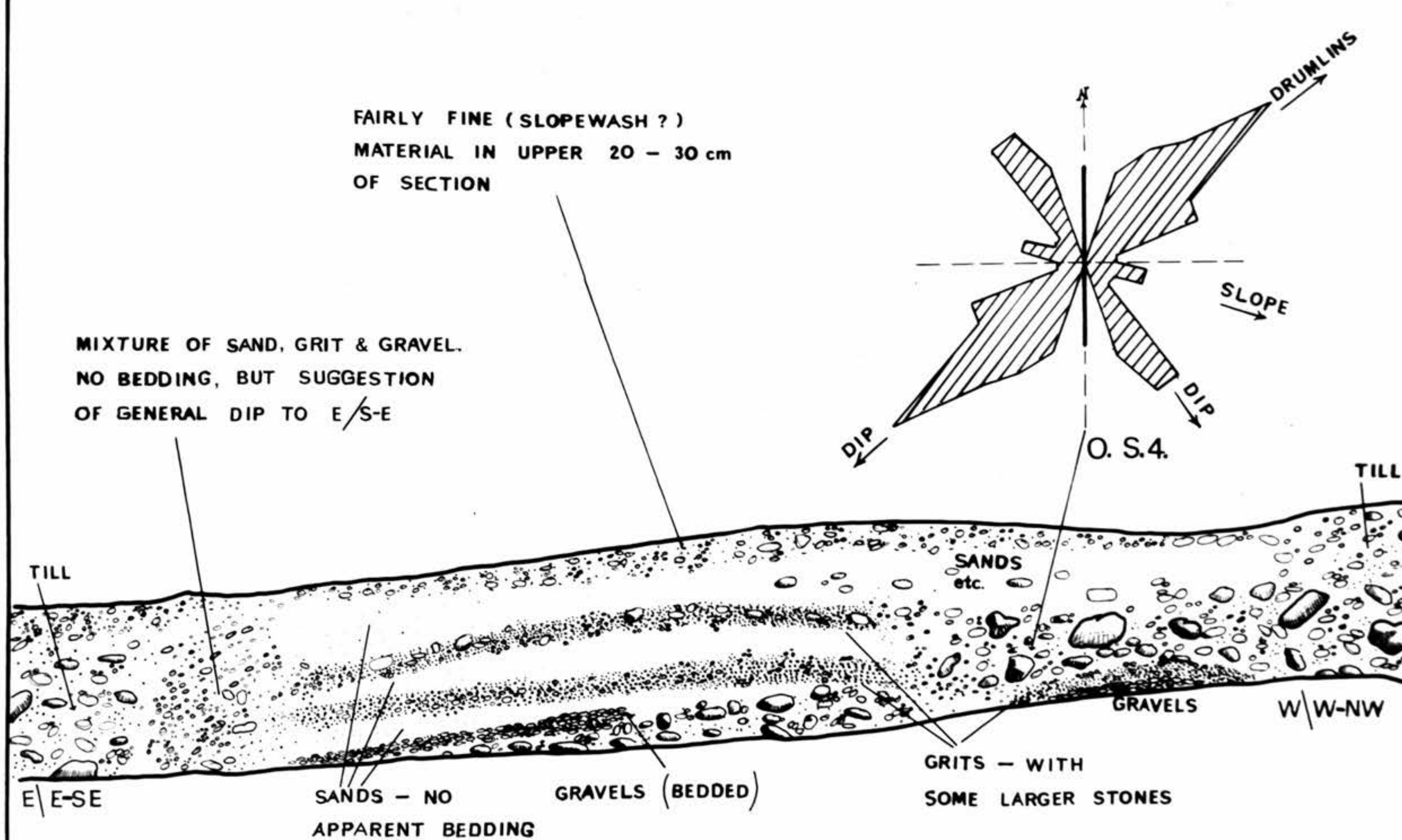


FIG 15[C] M.R. 721424 (BASALT AREA)

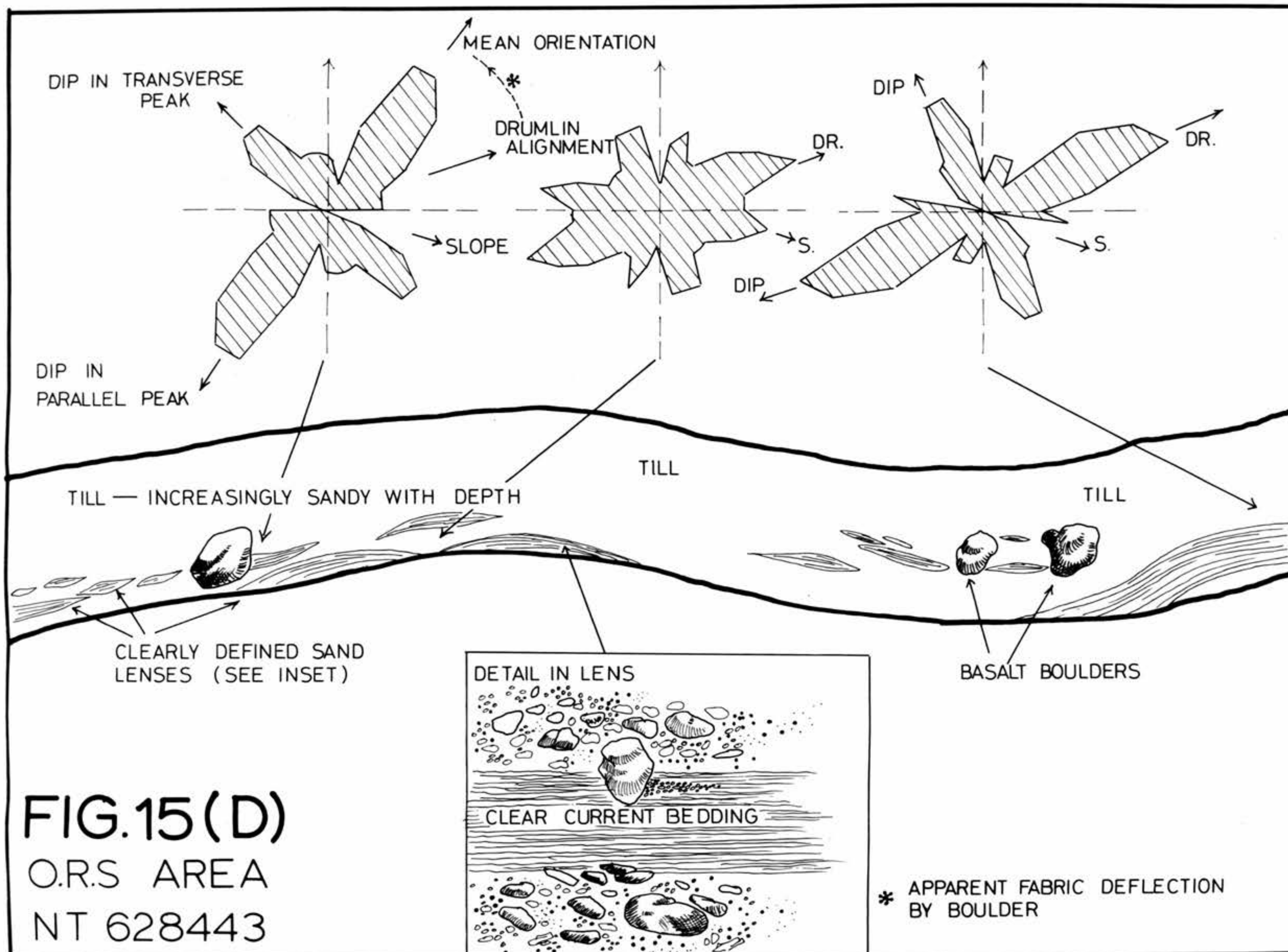


FIG.15(D)
O.R.S AREA
NT 628443

would later produce the considerable faulting and contortions noted. The sands and gravels formed within the basal ice would likewise be subject to modifications of stratigraphy as they were released.

Where sand and gravel sequences do not reach the surface in the sections examined the upper deposit is a till. This has the appearance of a lodgement till yet in its mode of origin it is essentially ablation. It may contain greater or lesser amounts of small grit or sand lenses No re-activation of the ice is envisaged after deposition of the sand and gravel sequences. Indeed considerable evidence to the contrary will be presented.

Some of the locations at which the above features were noted will now be considered. Figs. 15a and 15b illustrate sections in the Carboniferous bedrock area north of Eccles village on the large double-tailed feature referred to previously. (~~M.~~R. NT 757418). The diagrams are largely self explanatory and no additional descriptions of the sand and gravel sequences is necessary. Sections were around 2 m in height and were drawn carefully to scale. Extensions to the base of Fig. 15a show where additional excavation was made to examine the sequence below the level of the trench. (More extensive excavation was not possible.) Fabric patterns examined in the tills close above sand and gravel sequences illustrate one aspect of the lodgement character of the upper till. Orientation O.S.1 is a particularly striking fabric pattern relating very closely to the fabric pattern shown by orientation O.23 (inset Fig.15b) O.23 is one of the basal series of fabric analyses made in tills here no sand and gravel interference could be detected and lies some 100 m to the east of the section illustrated, although still on the drumlin tail. The apparent confusion in orientation O.S.2 (Fig. 15a), on the other hand, is explicable in terms of slumpage and contortions at this point causing disturbance in the overlying till.

Possible reasons for this have already been suggested, (e.g. the meltout of ice fragments). Equally, orientation O.S.3 lies above fairly steeply plunging fluvioglacial deposits and likewise has lost most of any orientation it may have possessed. The original orientation is suggested as being inherited from the englacial transportational environment in a manner similar to that envisaged by such as Harrison (1957) and later workers. This fabric pattern is then preserved as the till is released from the heavily-laden basal ice unless subsequent slumpage disturbs the deposits. Such subsequent movement is noted in Figs. 15a and 15b in terms of the discontinuities, slumpages and contortions in the stratigraphy.

No characteristically recurring sequence of gradation from top to bottom of the section was ever noted, as one might have been led to expect from the views of Carruthers (1939). Rather the sand and gravel horizons appeared to be relatively haphazard, with sequences of sands, grits and gravels being arranged without apparent pattern.

Fig. 15c illustrates a similar pattern of occurrence in the lee of the main body of the Kelso Traps (~~M.R.~~ NT 723424). Here the deposits are shown as almost reaching the surface over part of the section, covered only by a very shallow and more recent slope-wash material. The intermixture of till and fluvioglacial material is very evident in this section. A strong fabric pattern is also shown in a till which overlies part of this fluvioglacial sequence. In this total section a sequence is suggested whereby water has been moving fairly quickly from the decaying ice along a definite path under or within the ice. This is now represented by the comparatively un-disturbed sand and gravel deposits in the centre of the section. At the edges of this sequence where support was formerly afforded by heavily-laden dead ice slumpage and distortion have occurred with the melting of this ice and the junction with the surrounding melt-out till is not a sharp one.

Fig. 15d illustrates the other major type of sub-surface occurrence of fluvioglacial deposits, namely the well-defined and largely undisturbed sand lenses on the tail of Knock Hill. These sand lenses have already been described and little further description is necessary in view of the diagram. The upper, Silurian-dominated till is essentially lodgement in appearance in terms of the high "fine" content, the lack of angular stones, the lack of any sorting and the strong fabric patterns (Fig 15d), yet in this case it must again be seen as originating from stagnant ice. The current-bedding patterns in the lenses are not disturbed at their junction with this upper till and the well-reserved nature of the lenses suggests no movement of the ice sheet subsequent to their deposition. It was notable that the bedding pattern did not run horizontally according to gravitational forces but parelleled the slope of the tail feature. This suggests sub-glacial pressure controls. The lenses are seen as having originated by gradual squeeze melt with water movement gradually being concentrated into a few major avenues of movement resulting in these bigger lenses. (The possibility of cavities has already been suggested.) Details within the lenses (inset, Fig 15d) suggest the gradual let down of this upper till, one particular example showing a boulder jutting down from, or dropped from, the upper till with the sands apparently built up around it without interuption of the pattern of bedding. The fabric patterns again point to this retention of orientations inherited in the transportational environment. Orientation O.S.7 is less than convincing on this, a preferred orientation approximately in the direction of slope being indicated. O.S.5 however is a very clear pattern with well-developed parallel and transverse peaks. O.S.6 at first sight appears to deviate from the true direction of ice movement but this appears explicable in that the orientation was taken literally up against a massive basalt boulder. This boulder appears to have locally deflected the fabric pattern northwards with movement in the englacial environment.

Having thus examined in detail, locations which typify this undermelt process in the study area, it is possible to cite more general lines of evidence which support the idea of widespread melting <u>in situ</u>. These factors apparently suggest ice sheet stagnation over much of the Tweed basin. Among the more significant lines of evidence are the following;

(a) lack of moraines indicating any halt or retreat stages,

(b) the spread of surface gravels and sands in the inter-drumlin depressions, often showing a degree of ice control, yet no pattern existing in these (e.g. grading) to suggest the retreat of an ice front,

(c) evidence of the presence of massive ice bodies controlling the final melt in marginal areas, e.g. Sissons (unpublished) in the area of Branxton village, south-west of Coldstream (reference chapter 1),

(d) many of the sub-surface sand and gravel sequences (as well as surface fluvioglacial forms, e.g. the Gala Law esker, ~~UK~~ NT 705355 to 717363) are found in relatively high positions, suggesting control by something other than gravity and pointing to former widespread stagnation of an ice sheet. Many of these sand and gravel occurrences have no surface expressions but have been covered by later deposition from within a dead-ice mass.

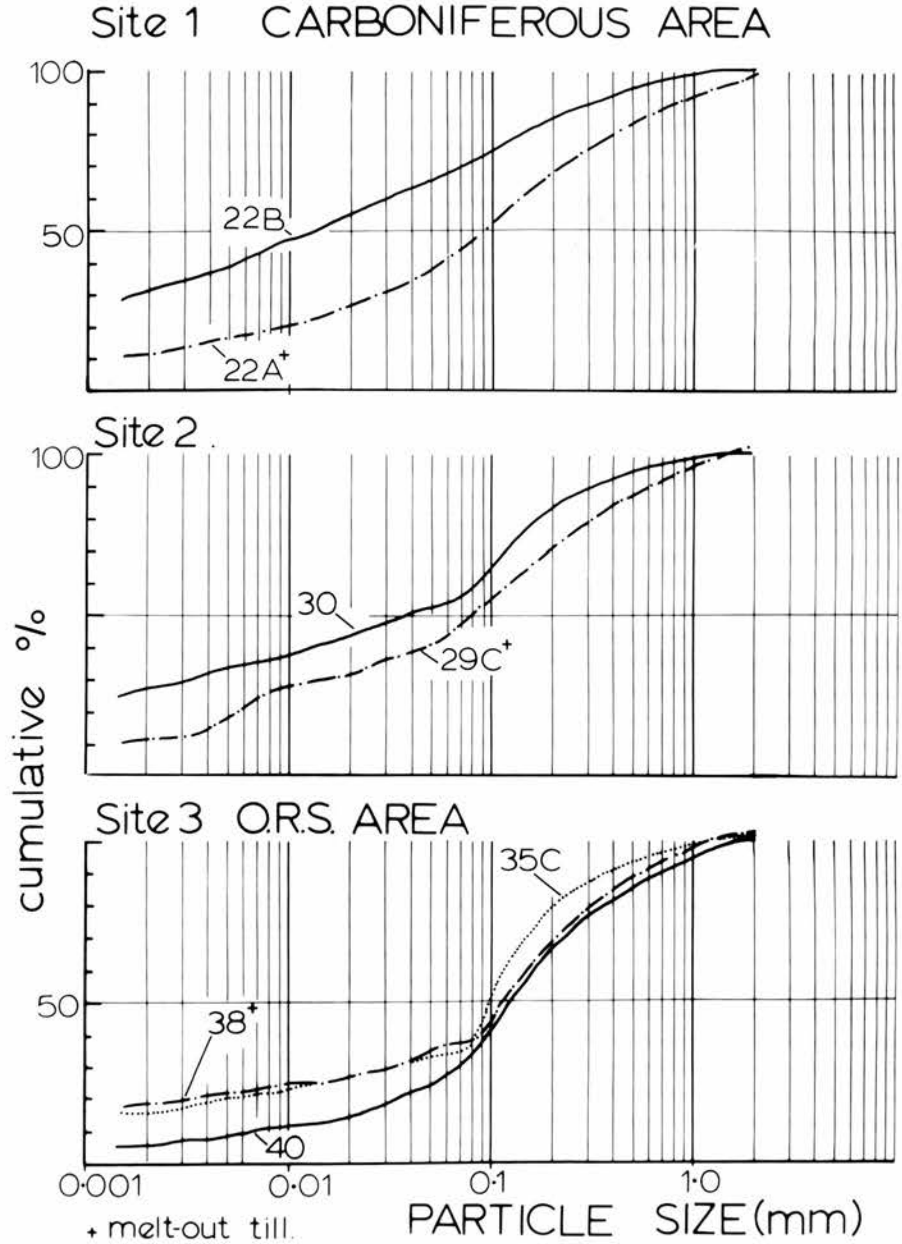
Over much of the area there was no evidence of sand or gravel at least in the 2 + m of section examined and no distinction was possible between any upper and lower tills, other than gradual changes due to erratic content, colour etc. It is possible in these areas that a form of ablation till does exist but that straightforward melt-out en bloc has produced a till no different in general appearance and character from a true lodgement till. While bottom melt or undermelt is seen as the agency responsible for the sand and gravel sequences and most of the so-called "upper" or "melt-out" till, it is recognised that some degree of topmelt must have occurred as stagnation progressed. This is suggested as being of lesser importance in the formation of the bulk of the deposits referred to above, although possibly more important in the production of the waters which produced the surface sands and gravels. It is however, difficult to estimate at what point topmelt began to play its part in the depositional sequence under examination. From the evidence examined this effect seems minimal.

Stone-counts and "pebble" counts (erratics approximately 1 to 1.5 cm in diameter) will be discussed in subsequent chapters in further examination of this final deposition phase but it is relevant to consider here the evidence of particle size analysis. Two sites were examined in the Carboniferous bedrock area.

The first site lay on the tail of the large drumlin near Eccles village (Figs. 15a and 15b). The second site lay very close to the junction between basalt and Carboniferous bedrock areas (~~M.R.~~ NT 726422). The results are shown in Fig. 16. (Differences in erratic content between till samples at any one site will subsequently be shown to be minimal.)

Both these sites show decreases (up to 20%) in the clay fraction in the melt-out till and consequent increases in the sand fractions (up to 26%). Differences are especially marked in the Eccles site where it is significant that the sand, grit and gravel sequences associated

FIG.16 PARTICLE SIZE ANALYSIS : A comparison between basal and melt-out tills.



with melt-out are especially well developed. The silt showing a fall of 5.5% in the surface sample and the second site a rise of 8%. The most likely explanation of the relative coarseness of the upper samples must lie in this squeeze melt to which they have been subjected since no marked difference in origins of material was noted. Carruthers (1939) and later workers have pointed to this clay loss as an early stage in the process. Although no evidence of laminated clays existed in the section this does not disprove the existance of such a process.

It is not envisaged however that all melt-out tills need necessarily be recognisable by this relative poverty in the clay fraction as compared to basal tills. A third site was examined in the Old Red Sandstone bedrock area in the basin down-ice of the East Gordon ridge (Fig. 2, ~~M.R.~~ NT 689429). This produced evidence of higher clay percentages in the known melt-out till compared to the two samples of apparent lodgement till. Results are shown in Fig. 16. Here sand, silt and clay percentages are not greatly different between S.38, a melt-out till, and S.35C, while the lowest clay percentage of all is recorded in S.40, a basal till lying fairly close to Old Red Sandstone bedrock. Although it is possible that some "washing" of the melt-out till has taken place during deposition (and indeed squeezing of the basal till also), it has not in this case produced differences between the two tills upon which any classification could be made. Lithological variations are probably the major controls in this instance. It seems therefore that particle size analysis alone is not a reliable index as to whether a till is a true lodgement till or a potential melt-out till. It is submitted, however, that the evidence presented does lend further weight to the undermelt theories discussed in this chapter.

6. <u>BEDROCK IN THE SECTION</u>

1. <u>Carboniferous</u>. Other than in the two meltwater channels already

illustrated (Figs. 14a and 14b), there were only two sites where bedrock was noted in the Carboniferous part of the section. The first (Fig. 35) showed almost two metres of shattered shales, black to brown in colour lying on low ground below the stoss end of a large drumlin (of over 3 km in length) near Castlelaw Farm (N.R. NT 815425). A thin grey-brown till of some 25% Carboniferous erratic content (falling off rapidly towards the surface) covered this shattered bedrock with a colour graduation from one to the other over about 30 cm. Carboniferous were mainly sandstone, not shale.

The second bedrock occurrence was of green micaceous sandstone on the ridge east of Hume village referred to previously (Fig. 17a). Here solid bedrock was noted over a stretch of 60 to 70 m but even here it was often difficult to discern solid bedrock from the ever-present "intermediate till zone". In this intermediate zone, slabs of local sandstone up to one metre in length lay in a matrix of sandstone fragments in varying degrees of decomposition, diminishing to fine sands nearer the surface. The change upwards into a till dominated in colour and petrology by basalts and to a lesser extent Silurian erratics was a gradual one and the impression gained was of one compact basal till. No recognisable ablation material was detected on this high, open site where glacial erosion had been very active.

2. Old Red Sandstone. In the Old Red Sandstone area the sedimentary rocks, mainly sandstones, were often visible within the two metres or so of the section. In this relatively limited depth it was the "intermediate till zone" of excessively fragmented local rock which was most apparent. The thickness of this zone varied from less than one metre to over two metres. Reasons for such variation are not immediately apparent. Possible explanations lie in:-

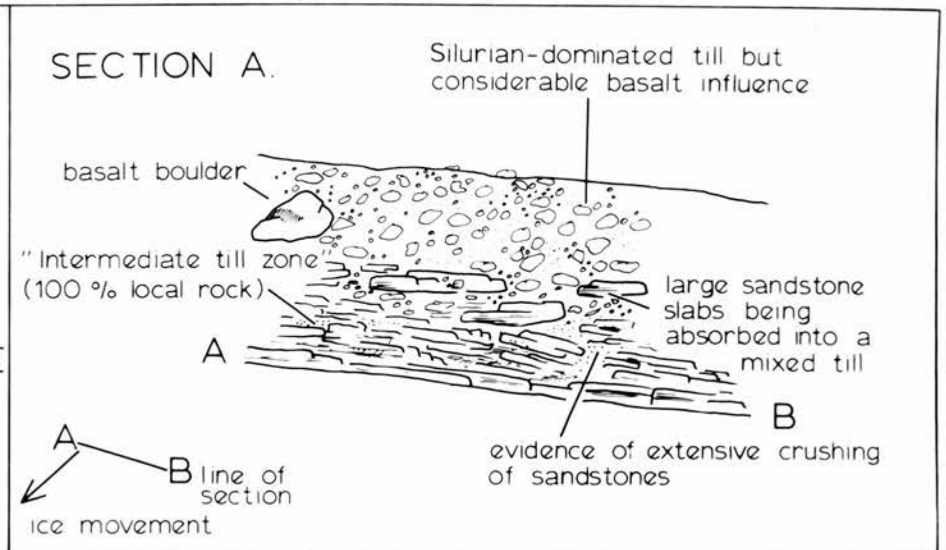
(a) differences in the structure (e.g. jointing) of the different

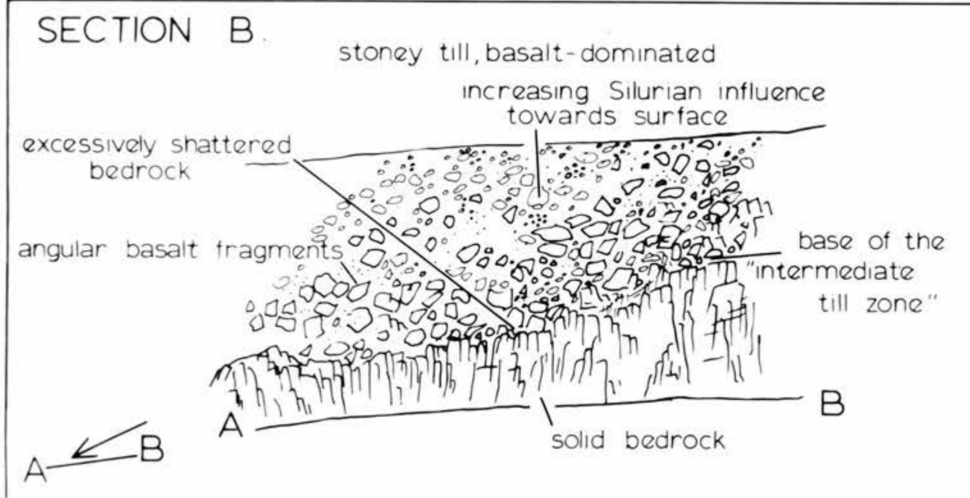
FIG. 17. SELECTED BEDROCK EXPOSURES WITHIN THE PIPELINE SECTION.

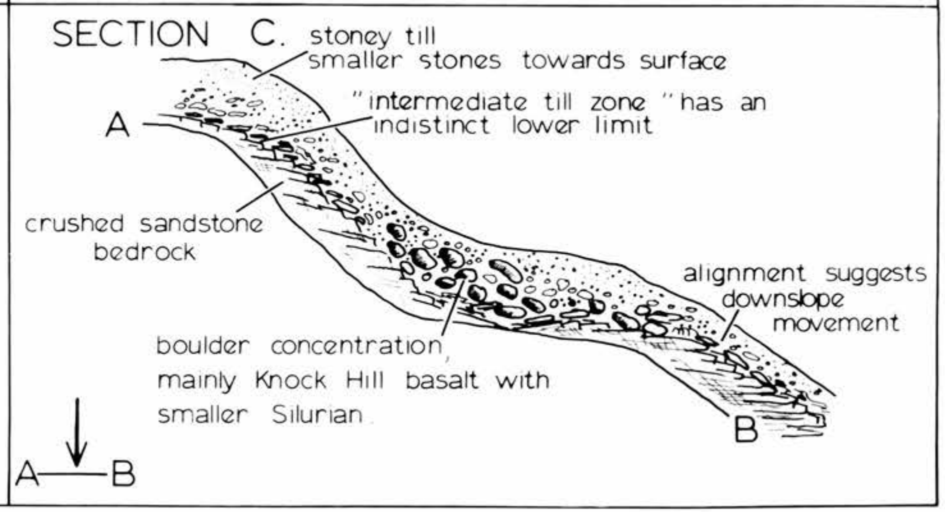
A : CARBONIFEROUS SANDSTONE IN THE AREA OF SAMPLE Rd.X12B (NT736419)

B : OLD RED SANDSTONE SANDSTONE ON THE STEEP (N) FLANK OF KNOCK HILL (NT620447)

C : BASALT BEDROCK IN THE AREA OF SAMPLE S.32 (NT717423)







beds. This is possibly of more limited relevance in the weakly-cemented Old Red Sandstone rocks.

(b) differences in the intensity of glacial erosion with differences in position, slope, aspect etc. E.g. compare Fig. 17b with Fig. 10.

(c) differences in exposure to periglacial activity prior to and following, glacial erosion. This is not to say that periglacial conditions would be experienced during ice decay but rather during the Loch Lomond re-advance when ice did not reach the Tweed basin. Periglacial activity is in turn dependant on a variety of factors, not least being the availability of water for example. The deeply shattered shales near Castlelaw Farm are perhaps an instance of this in a low site.

3. <u>The Basalt Lavas</u>. Bedrock is apparent almost continuously along the section where it crosses the high parts of the basalt (Fig. 17c). Higher on the lavas and away from the section bedrock is exposed at the surface, (e.g. Hume and Smailholm areas) although even on the relatively lower ground crossed by the section, (maximum c. 180 m O.D.) bedrock was never more than 2 m below the surface and frequently rather less. The rock is quite shattered in parts, again potentially with some periglacial activity having assisted this at some period. The intermediate zone, (strictly a till), appears shallower than that associated with the sedimentary rocks. It is normally not more than one metre deep but this again varies locally, rising to 1.5 m at some locations on the lee side of the basalt body. This layer and the lower horizons of overlying till are characterised by angular fragments of basalt in a gritty matrix, the latter often quite limited. The physical break up of the basalt appeared quite considerable in this area and fragments were dominantly under 25 cm in their 'a' axes. Particle size analyses have also shown that the basalts appear to produce high

clay percentages in the till matrix and appreciable silt percentages despite this sometimes gritty appearance of the general mass.

CHAPTER THREE

RESULTS OF STONE-COUNTS FROM THE BASE OF THE TRENCH SECTION

The trench and some of its inadequacies have already been described in relation to chapter two. In the interpretation of stone count results from this trench, some difficulty also lay in the fact that sites did not lie directly down-ice of each other.

The Sample Technique

A complete sample of till was taken from the solid floor of the trench or, where this was not possible, from the base of the trench wall. Depth was noted in each case. No absolute control was imposed on the size of sample in the field. It was generally in the region of 0.01 cubic metres. The sample was taken back into the laboratory, partially broken down by hand and then dried. Separation of the macro-particles of the dried till was completed using a rubber-covered mortar and pestle. This process was necessarily a very slow and careful one since small fragments of sandstone in the till were often easily destroyed. Where break-up did occur, the larger rotted fragments were measured and their volume and thence weight calculated. Smaller fragments destroyed in this process were given a nominal weight of 5 gms if large enough to be included in the final count. The remainder of the sample was then passed through a 16 mm seive. Since the technique of stone identification was also to be used in the field, only a hard lens was used and this 16 mm size was about the minimum for reliable recognition under such circumstances. Because of the technique of sampling some variability was therefore to be expected in the number of stones counted at each site. Of the 49 samples in this sequence from the base of the trench the distribution in terms of size was as follows:-

No. of Stones	No. of Samples	
under 30	0	(0%)
30-49	1	(2%)
50-69	9	(18.4%)
70-89	25	(51.0%)
90-110	12	(24.5%)
over 110	2	(4.2%)

The average size of stone count in this sequence was just over 82 stones per site. The median was 82 and modal values were 82 and 100.

Rock Groups Identified

The following groupings were used in the stone-count classification.

1. Silurian: As already suggested (chapter one), no sub-division of the Silurian erratics was practicable. Erratics were dominated by varieties of greywacke but grits and occasional shales also occurred.
2. Old Red Sandstone: This sedimentary group was dominated by pink or red varieties of sandstone.
3. Basalts: It has already been noted that it was considered impracticable to distinguish between intrusives and extrusives (chapter one). This group therefore includes all basalts.
4. Carboniferous: This sedimentary group is again dominated by sandstones, mainly of a micaceous character.
5. Trachyte-Felsite group: This general group covers the acid intrusives described in chapter one. These outcrop mainly in the Melrose-Earlston area.
6. Vent types, Agglomerate: This group includes erratics from the many small pipes and vents which exist as well as from major features like the great agglomerate neck of Fans Hill near Earlston. Recognition of these involved particularly questions of crystal

size and development as well as composition.

7. Vein Rocks: This group was dominated by varieties of quartz.

8. Cheviot Andesites: These are the characteristically porphyritic andesitic lavas of the Cheviot group.

9. 'Others' category: This included in a few cases, stones not recognised by the author but more commonly included small fragments which were too weathered for recognition.

Methods of Study

Stones in the 16∅ mm and over size range were classified according to the above groupings. Numbers in each category were recorded and expressed as a percentage of the total stone population in each sample. Weight of stones in each category was noted for each sample and volume was measured by a simple displacement method. It was subsequently found of little value to measure both weight and volume as differences between percentage weight and percentage volume were insignificant, especially when related to percentage numbers (Fig. 18). Weight and number only were then considered.

Stone Count Results

Fig. 19 illustrates the complete pattern of results expressed in terms of percentages. Before considering more closely the behaviour of some of the various erratics it is advisable to refer to the general pattern of till composition. This is best done by reference to geological area.

The Tills of the Old Red Sandstone area

In considering the tills of the Old Red area a problem of derivation exists in the presence of the Old Red conglomerates of Lauderdale where an alternative source of greywackes to the Silurian is found. These conglomerates are dominantly composed of cobbles and pebbles of greywacke

FIG. 18. A COMPARISON OF %WEIGHT, VOLUME & NUMBERS OF ERRATICS AT SELECTED SITES.

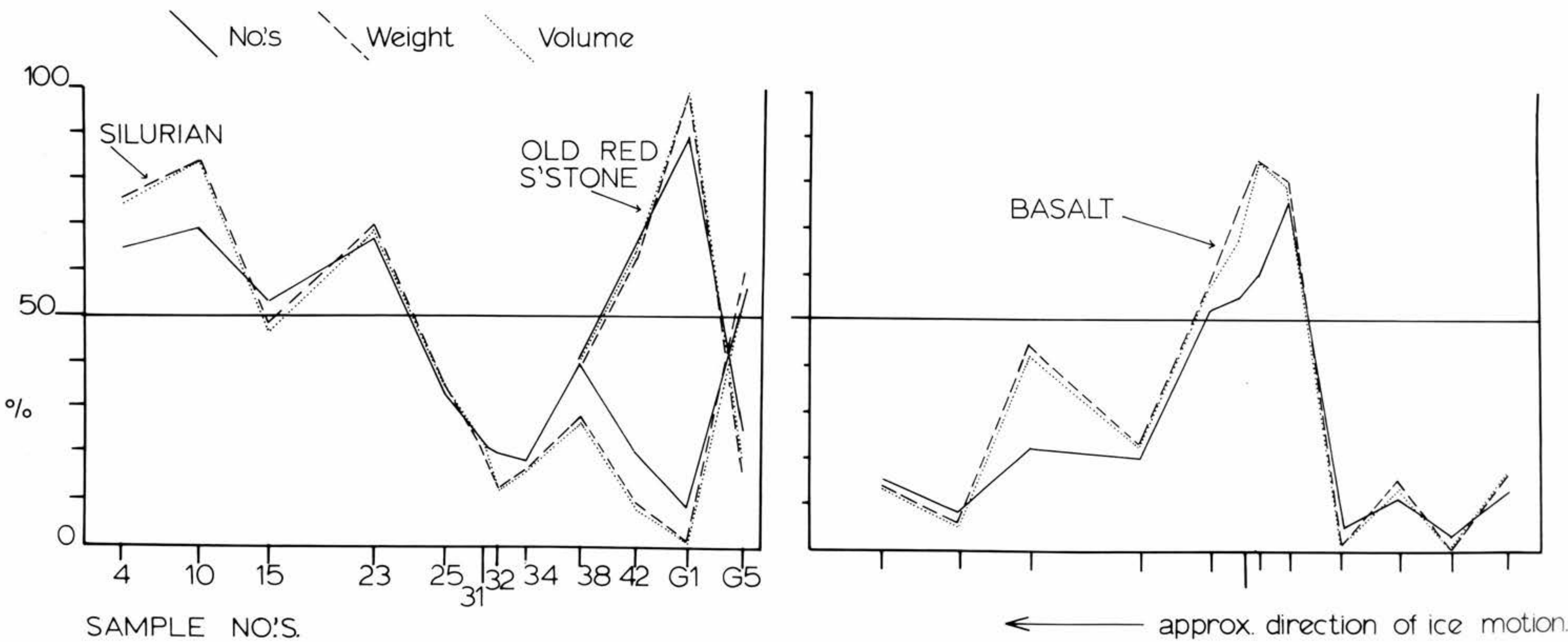
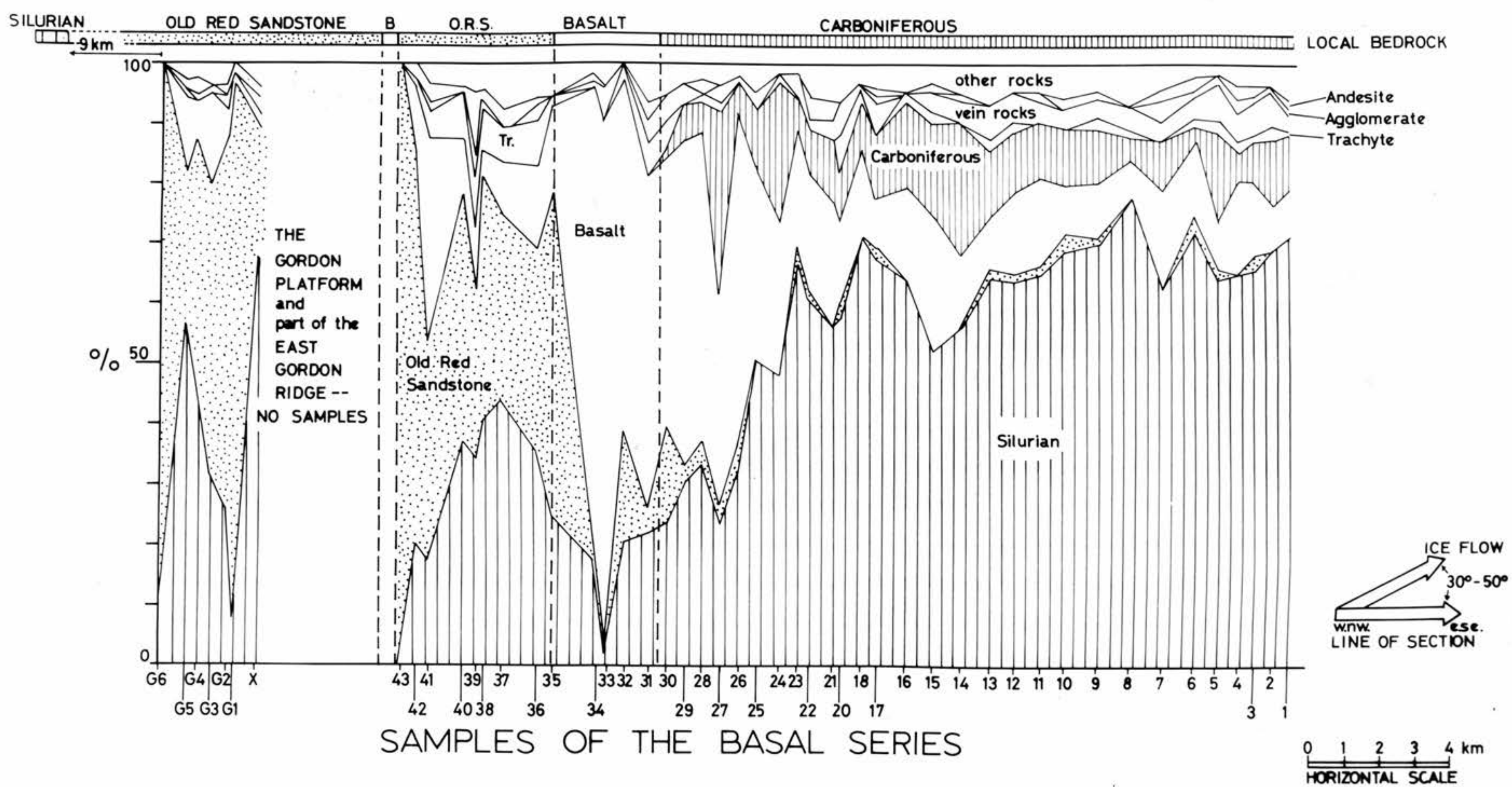


FIG. 19 TILL COMPOSITION

Erratics in % numbers



in a red-coloured matrix (Fig. 2). It was not generally possible to recognise greywackes derived from these conglomerates as distinct from Silurian erratics. The extreme rounding of the cobbles found in the conglomerates was not a reliable guide as investigations revealed evidence of much secondary fracturing, break-up and re-shaping of these cobbles on incorporation into tills. On the other hand an examination of Silurian-derived greywackes in tills south of Lauderdale revealed quantities of well-rounded stones. (The potential influence of these conglomerate-derived greywackes diminishes on moving eastwards in the section where ice movement as suggested by the alignment of ice-moulded forms indicates a passage of these erratics to the north of the section line.)

Stone-counts in the Old Red area are dominated by varying proportions of the local bedrock and the Silurian erratics, mainly greywackes. The relationship of these two groups would appear to depend largely upon the depth to bedrock at any point i.e. the depth of till. Bedrock is close to the surface in the thinner tills on the tail of Knock Hill for instance (Fig. 10 ; Fig. 17b), and counts of Old Red Sandstone vary from 25% to 95% dependant upon this. Farther east on the part of the Gordon Platform crossed by the section a count of almost 70% Silurian was recorded however and Old Red fell to nearer 20%. This occurred in a lower area of deeper and apparently stonier till which showed a darker and less reddish colour than that lying close to the Old Red bedrock. Greater Silurian influence is suggested all through this darker till.

This disappearance of Old Red erratics with vertical distance from bedrock has two possible explanations. Initially it might be thought that the Old Red fragments did not reach these higher levels in the till but were transported at lower levels in the ice or in till moving beneath ice. The influence of the Old Red on colour and fine content in many of these 'higher' tills of greater Silurian counts does not entirely agree with this idea however. It would seem rather that this apparent disappearance is more often the result of the relative weakness of the Old Red Sandstones and their susceptibility to abrasion during transport. Counts of a smaller size-fraction of stones in the till might therefore be expected to show increased proportions of the weaker rock. Studies were carried out on this over the whole area of investigation and results are examined in chapter five.

In many cases the Silurian erratics, like the Old Red fragments, tend to be quite small. Sandstone fragments over about 10 cm became relatively infrequent at as little as 1-2 metres above bedrock. It seems possible in some cases that the large greywackes found in these tills may be derived from the conglomerates in Lauderdale to the west with the great quantities of Silurian rocks being carried over the area in heavily laden ice and only being represented in the surface counts at most. It was not possible to test this hypothesis however.

Basalts also appear in the tills of the Old Red area. Percentages are generally small, though reaching 15% on the tail of Knock Hill. Knock Hill is an intrusive basalt body and the basalts found were fresh local fragments. In the low-lying depression east of the site of S.43 (N.T. 673434), more basalts are derived from the East Gordon ridge, a westwards extension of the Kelso Traps (Fig.2). A maximum of 33% basalt was noted just off the ridge crest (S.41) but out of the influence of this ridge basalts fall to 5-10% in the areas of samples S.37 to S.40. (The examination of the trench section on the East Gordon ridge suggested that this arm of lava was not as extensive as indicated by geological mapping (Geological Survey map by J. Geikie in late 19th century). Sample S.43 for example, showed not basalt but sandstone bedrock at a depth of about 2.5 m on the southern side of the ridge. North and west of this however some basalts are encountered as in the meltwater cut of the Eden Water as it comes off the Gordon Platform.) Basalts found to the west of Gordon were fresh varieties whereas those found in samples S.35 to 43 (Fig. 19) were of both fresh and weathered varieties.

Small quantities of trachyte, agglomerate and vein rocks complete the composition of tills in the Old Red area. In the east of the area, notably in the low area south of the ridge of lavas referred to above, trachytes become more evident, frequently reaching 7 or 8 %. Fragments of agglomerate from the various necks of the area generally contribute some 2-4% to the stone-counts of the till but in S.39 (N.T. 687429) a count of over 11% was recorded. This was of a very distinctive rock of large crystal development and was indicative of some pipe or small vent buried locally up-ice. Small fragments of a tuff or ash-like material were associated with some of these fragments. No vent or similar feature is indicated on any geological map of the area.

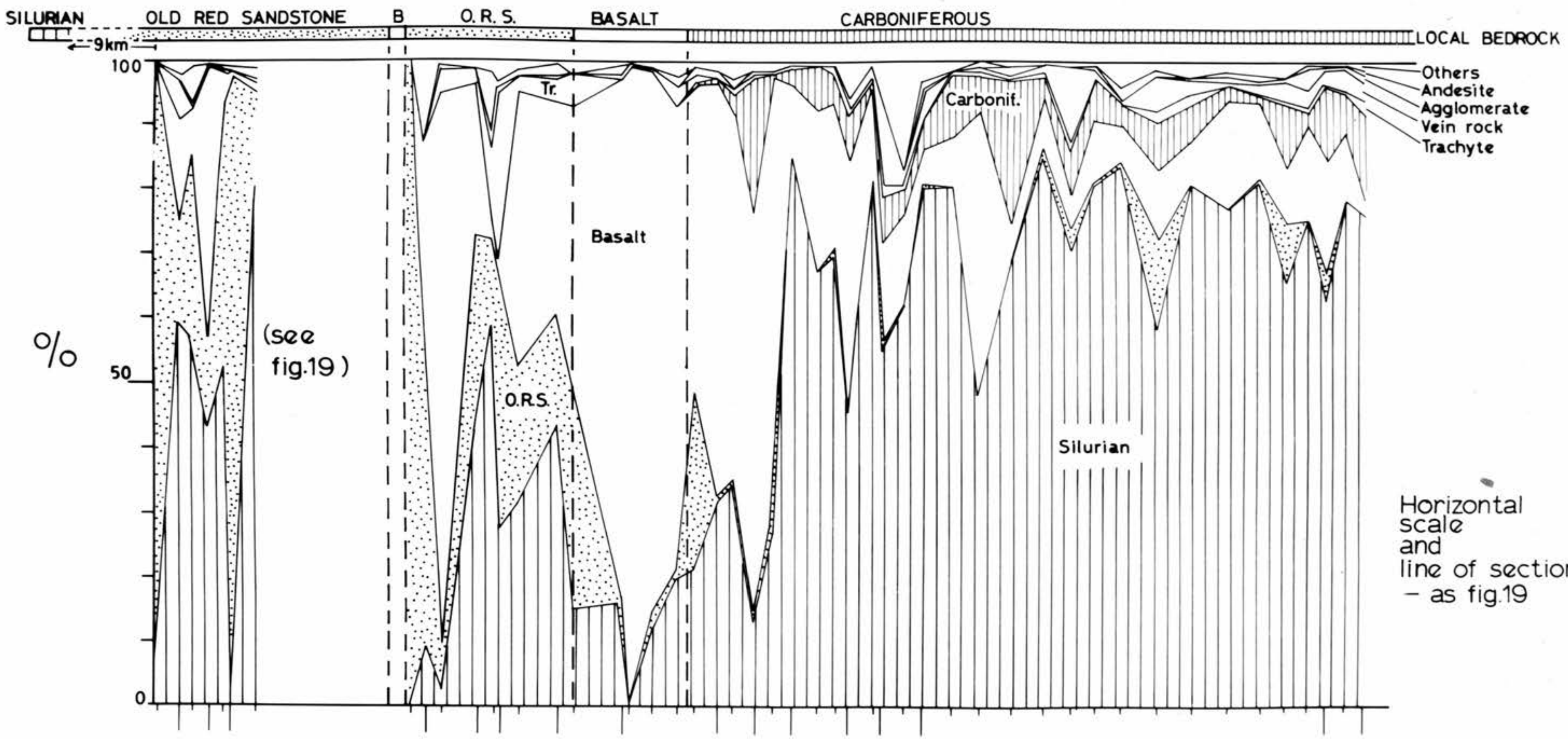
Tills of the Basalt area

Tills on the basalts tend to be even thinner in many locations and much influenced by the local bedrock. This is especially true of the higher areas and the immediate lee slopes. On the very high parts of the basalt outcrop till is often less than a metre in thickness and composed almost totally of angular basalt fragment. The base of the trench section, where not on solid or shattered bedrock, often approached 100% basalt counts. Fig 19 and Fig. 20 illustrate this dominance in these basal stone counts, a dominance which is especially marked when considering percentage weight or volume (Fig. 20).

Basalt fragments in the tills were generally very angular and often considerably fractured. The questions of weathered/fresh basalts has already been discussed in chapter one and it is sufficient to add that in samples S.31 and 33, both of which lie close to bedrock,

FIG. 20 TILL COMPOSITION

Erratics by % weight



SAMPLES OF THE BASAL SERIES - numbers as fig. 19

appreciable amounts of fresh basalt were noted, mixed in with the more typical weathered variety of basalt lava. Of a 66% basalt count in S. 31, 13% were of the fresh variety, and of about 90% basalt in S.33 about one third were of this fresh type.

Silurian rocks form the major secondary component of the macrofabric of the tills in this area, becoming more evident at lower altitudes and in lee sites. Over 20% Silurian was recorded in some of these lee localities crossed by the trench section. Greywackes again dominate the Silurian erratics which at higher levels in the sections in particular are often of quite small size (10 cm or less).

Old Red fragments fall off in frequency fairly rapidly down-ice of the Old Red area, being generally under 10% over most of the basalt area examined. The basalt in this area is of course of considerable extent and altitude and this would appear to be an important factor in the rapid fall in the Old Red count. There is evidence for example that more Old Red survives where the basalt presents a less imposing physical barrier. This is seen in the basalts of the central part of the Tweed valley around Makerstoun (Fig. 2) and is reflected in a greater sandstone influence down-ice of this. (Ragg et al., 1960). This is also apparently reflected as far down-ice as the stone-counts in the area north of Coldstream (S.1 to S.10; Fig. 20). There is also a greater influence of Silurian rocks immediately down-ice of this basalt "gap" and a relative drop in basalt percentages. It may be that this lesser basalt contribution is apparent rather than real and may only reflect a greater Silurian and Old Red influence locally without any quantatitive lessening in basalt contribution. Certainly in the counts of basalts down-ice of this in the area north of Coldstream there is no evidence of a fall in basalts to correspond with this gap. Equally however, it is not known how much this might be masked by contributions from the basalt ridge running to the south of the Tweed. This is discussed later.

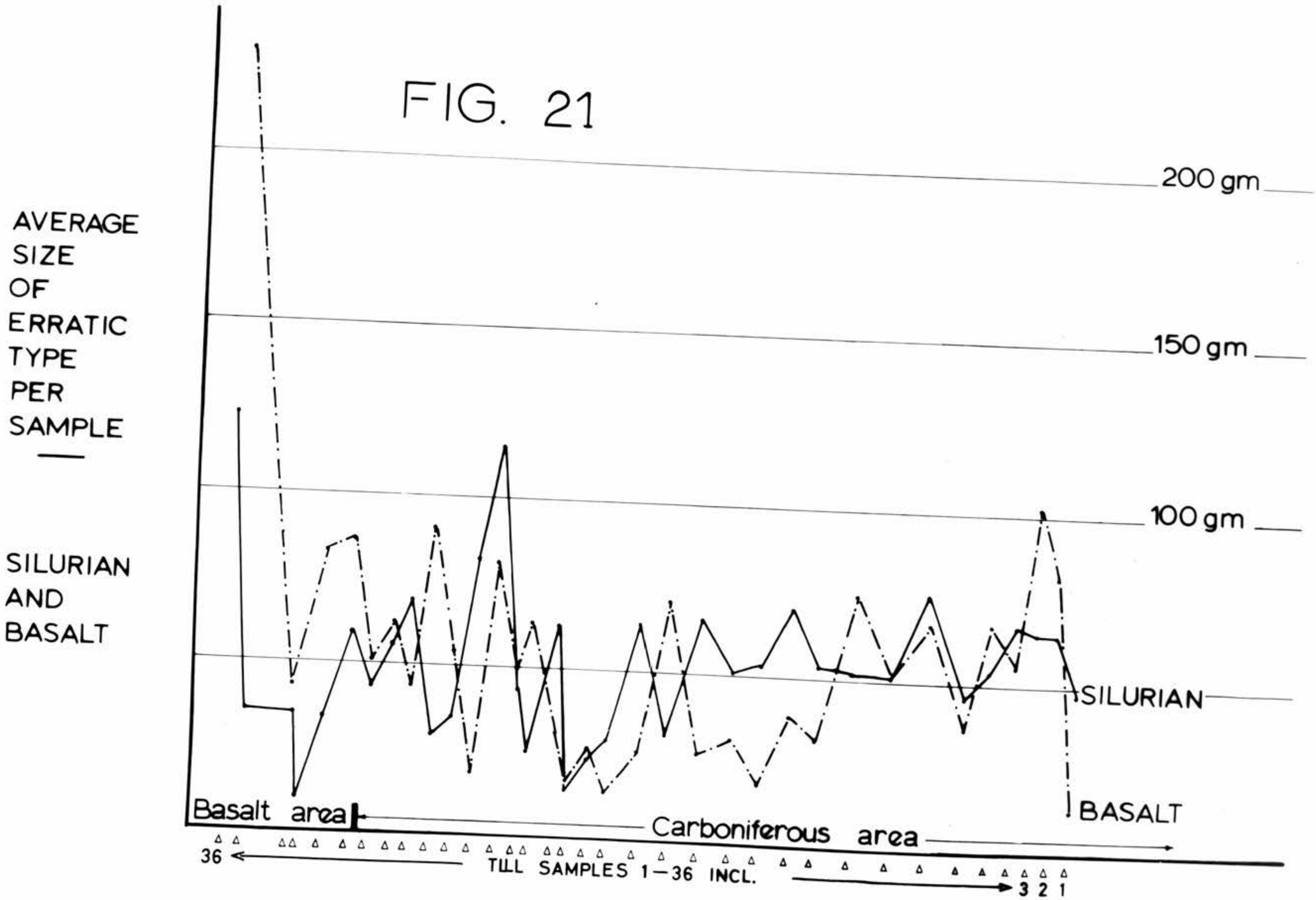
Small quantities of trachyte, agglomerate and some varieties of quartz make up the remainder of the till on the basalt area. These are generally in small amounts (under 5%) and even less significant in terms of volume or weight.

The tills of the Carboniferous area

Stone counts on tills in this area are very much dominated by high percentages of Silurian greywackes, up to 78% by number and 86% by weight being recorded in this trench sequence. The greywackes show a variety of size up to quite large stones, commonly over 12 cm and often much more. No Silurian boulders are found. Nearly all Silurian erratics show a high degree of rounding except where secondary fracturing has occurred during transport and discoid and ovoid shapes are particularly common. A general increase in Silurian percentage is noted in an easterly direction within the study area. This varies initially with the decline in basalt influence and locally may depend upon the depth to Carboniferous bedrock, (as seen in sample S.27, Fig. 19 for example).

The question of basalt counts is an interesting one. From about 50% basalt concentration low on the down-ice fringe of the lavas (S.30 -31, Fig. 19) the count gradually declines with minor oscillations to reach some 10% at 8 to 10 km down-ice of the source (S.10, N.T. 811425). A minor recovery is then suggested, especially by Fig. 20 and this may be due to some effect from the basalt arm running north-east from Kelso on the south side of the Tweed (Fig. 2). The variation appears slight however (and arguably well within any sampling error which might be involved) and suggestive at most of a fairly limited influence. Alternatively, as suggested above, this slight increase may be more important than at first suspected and may conceal a potential basalt decline in the lee of the gap in the centre of the valley referred to previously. Fig 21 shows the average basalt size per sample over the

FIG. 21


AVERAGE
SIZE
OF
ERRATIC
TYPE
PER
SAMPLE
SILURIAN
AND
BASALT
200 gm
150 gm
100 gm
SILURIAN
BASALT
Basalt area
Carboniferous area
36
TILL SAMPLES 1—36 INCL.
3 2 1

Carboniferous area and an increase is also reflected here in those early samples after a general fall from S.21 to S.10.

Carboniferous rocks reach a maximum of 30% concentration in a mixed till in this sequence from the trench base. This is found on a ridge of greenish micaceous sandstone east of Hume village. It would have been possible to count nearer 100% Carboniferous at locations on this ridge however, as bedrock lay less than two metres from the surface in many parts (Fig. 17a). Over the rest of the trench section Carboniferous bedrock was generally not apparent and Carboniferous counts ranged from 3% to 20%, being 10% or less in most samples.
Sandstones were the dominant erratics but fragments of shales, marls, limestone and even coal were found.

Vein rocks, mainly varieties of quartz, make up generally 4-5% of the till and the remainder is supplied by small quantities of agglomerate trachyte and in the east of the area some andesitic lavas. The occurrence of the lavas only in the early stone counts and the relatively marginal position of the source are good guides to patterns of regional ice movement in the Tweed basin. This is illustrated in Fig. 22 for example and shows the northwards deflection of east-ward moving ice by the Cheviot mass, at that time supporting its own independent ice cap (Clapperton, 1970).

A comparison of weight and number of erratics

A comparison between Fig. 19 and Fig. 20 is interesting. A consideration of percentage weight as opposed to percentage numbers has the effect of decreasing the proportions of Old Red Sandstone rocks in the tills, even within its own bedrock area, (except in a few samples on or very close to bedrock). This indicates the relatively small size of many of the Old Red erratics and the rapid break-down of the sedimentary rocks in the glacial environment. Basalt percentages on the other hand are greatly increased in a consideration of weight (or volume), at least in the basalt bedrock area and immediately down-ice of it. The angular basalt fragments in these areas are undoubtedly quite large but perhaps equally significant would be the small size of the Old Red and even some Silurian erratics to be found at low levels in these shallower tills. Farther east on to the Carboniferous area basalt percentages by weight decline even farther than their numerical equivalents though showing this recovery in the early samples as already discussed. This fall is accompanied by an even greater dominance of the Silurian, often to over 80% by weight. (Up-ice of the Carboniferous area Silurian percentages do not vary greatly between weight and numbers. The change in the Old Red count for example is largely measured against change in the basalt.)

Carboniferous percentages fall off markedly on the whole when considering weight again indicative of the considerable break-down of the sedimentary erratics and in this case also of the depth of till overlying bedrock. Percentages of the other minor till constituents generally show a decline when weight is considered although exceptions do exist. This is especially noted in terms of fragments of quartz which are often of considerable size.

<u>The problem of the Silurian erratics.</u>

It was suggested in chapter two that areas of greater and lesser stone concentrations occur apparently without pattern throughout the Carboniferous area in particular and all areas in general, probably in response to variations in former glacial conditions. These fluctuations would tend to cause oscillations which would complicate any attempt to note trends in stone size, (e.g. the fall off in both basalts and Silurian in samples S.20 and S.18 in Fig. 21 is indicative of this). Despite this a pattern still appeared detectable in the case of the basalts as described previously. This also appears true of the Silurian.

An average size per sample of between 50 and 75 gm was noted consistently in Silurian erratics over the Carboniferous area for example. This average covers a variety of stone sizes of course but also shows that this high Silurian percentage is achieved by a supply of consistently sizable stones. The distribution of Silurian erratics is possibly the major enigma of the tills studied in this area, especially in this direct relationship between amount of erratics and distance from source as noted over the Carboniferous area (Fig. 19). Before discussing this however the problem can be approached by considering the apparent lack of Silurian erratics over the Old Red Sandstone and basalt area. This idea must be qualified on two accounts however.

Firstly, the pipeline studies in these areas deal with limited regions of a relatively high and slightly marginal location in which local bedrock appears particularly prominent. Tills are often quite shallow and suggestive of fairly stong local influences. Where deeper tills are to be found Silurian erratics become more evident (e.g. Sample X). Towards the centre of the Tweed valley near Newtown, St. Boswells for example deeper tills are more common and Silurian influence correspondingly greater, notably in the upper one or two metres.

Secondly, in the pipeline section Silurian influence was generally to be found in the upper few tens of centimetres or in many cases the only significant Silurian concentrations were to be found on the surface where the larger Silurian erratics tended to occur (ref. chapter four). These are not represented in the results in Fig. 19 and Fig. 20 of course. Silurian erratics were also markedly absent from even the higher parts of the basalts in much of the pipeline section. Again the only significant occurrences were often on the surfaces of fields on some of the higher parts. Even here counts might be small (chapter four).

As the basalt influence gradually diminished into the Carboniferous area Silurian percentages and stone size regularly reached proportions greater than hitherto recognised. Yet this occurred down-ice of areas in which Silurian erratics were often markedly absent in any quantities It seems apparent from the evidence therefore that considerable quantities of Silurian material were carried within the ice for considerable distances over the Old Red and basalt areas. Real deposition in these areas only occured locally, generally in lower or sheltered sites recognisable today as areas of deeper and darker-coloured tills. Alternatively the only significant expression may be in the immediate surface layers where Silurian erratics were deposited during the last stages of ice movement or during final stagnation. This would seem to explain the pattern of Silurian erratics in areas up-ice of the Carboniferous area therefore. Details and theories of some of the glacial processes behind these ideas will be discussed more fully when all the evidence has been presented.

The next question that must be examined is why there should exist in the Carboniferous area such an abundance of Silurian erratics relative to the other till constituents. Several factors appear to play a part.

The differential resistance to erosion of the Silurian rocks and the sediments of Old Red Sandstone and Carboniferous age is undoubtedly a factor. It ensures that few Old Red erratics progress far to the east into the Carboniferous area to dilute the Silurian strength and equally that any Carboniferous erratics are also short-lived. In addition the tills of the Carboniferous area are for the most part fairly deep (ref. chapter two) and the influence of Carboniferous bed-rock is thus limited at these higher levels.

This argument cannot be applied to the basalts however. The basalt erratics are much more resistant to abrasion than the sediments and were actively eroded to bedrock by the ice in their exposed position and not protected by a till cover or a sheltered site. The fall off in basalt percentages down-ice as compared to the rise in the Silurian is explicable in three ways. Initially some dilution of the basalt erratics must have gone on as the basalt fragments were incorporated into the mass of Silurian debris already held at higher levels in the ice. Secondly, the basalt is much less extensive than any of the other major geological groups, especially in a direction parallel to ice flow, and although erosion appears to have been considerable there was not the opportunity to incorporate massive quantities of basalt into the basal ice. Thirdly, there is evidence to suggest that the role of the ice was beginning to change down-ice of the basalts and that deposition was becoming more important. This is suggested by the great depth of till, the sudden proliferation of drumlinoid features formed in drift and the increasing abundance of Silurian material to be found over the Carboniferous area. Basalts would not therefore have been incorporated so far along shear planes into the basal ice and not carried the great distances of the Silurian erratics. The greywackes would be found at higher levels than the basalt in the basal ice and consequently an increasing proportion of Silurian to basalt might be expected as one moved eastwards into the Carboniferous area. As the ice further slowed, thinned and deposited more debris this pattern would be emphasized. (The heavily-laden nature of this basal ice during the last stages of glaciation has already been suggested relating to the undermelt idea discussed in chapter two.)

The very great extent of Silurian rocks lying in the path of ice from the west was also undoubtedly a factor in the abundance of Silurian material incorporated into this ice (Fig.2). Equally important is the susceptibility of these rocks to being picked up by the ice.

The considerable scree developments visible in the area today suggest fairly well-jointed rocks and thus rocks susceptible to glacial plucking. The variable terrain of the Silurian area would enhance this process. Any jointing would also allow considerable freeze and thaw action on the strata under periglacial conditions prior to excavation by ice. Ragg and Bibby (1966), for example, have shown that greywackes in the Broad Law area were extremely susceptible to frost weathering. At the same time these fragments incorporated into the ice by plucking appear to possess considerable resistance to the abrasion process to which they would be subject during transportation. This results in the often sizeable and well-rounded fragments found deep into the Carboniferous area.

Finally attention should be drawn to Fig. 22. It will be noted from the introductory chapter on geology and from comments made in this chapter that for the most part erratics could not be attributable to point sources. In a few cases this was possible however and these are represented in Fig. 22. The implications of this pattern will be discussed more fully when all the stone-count sequences have been considered.

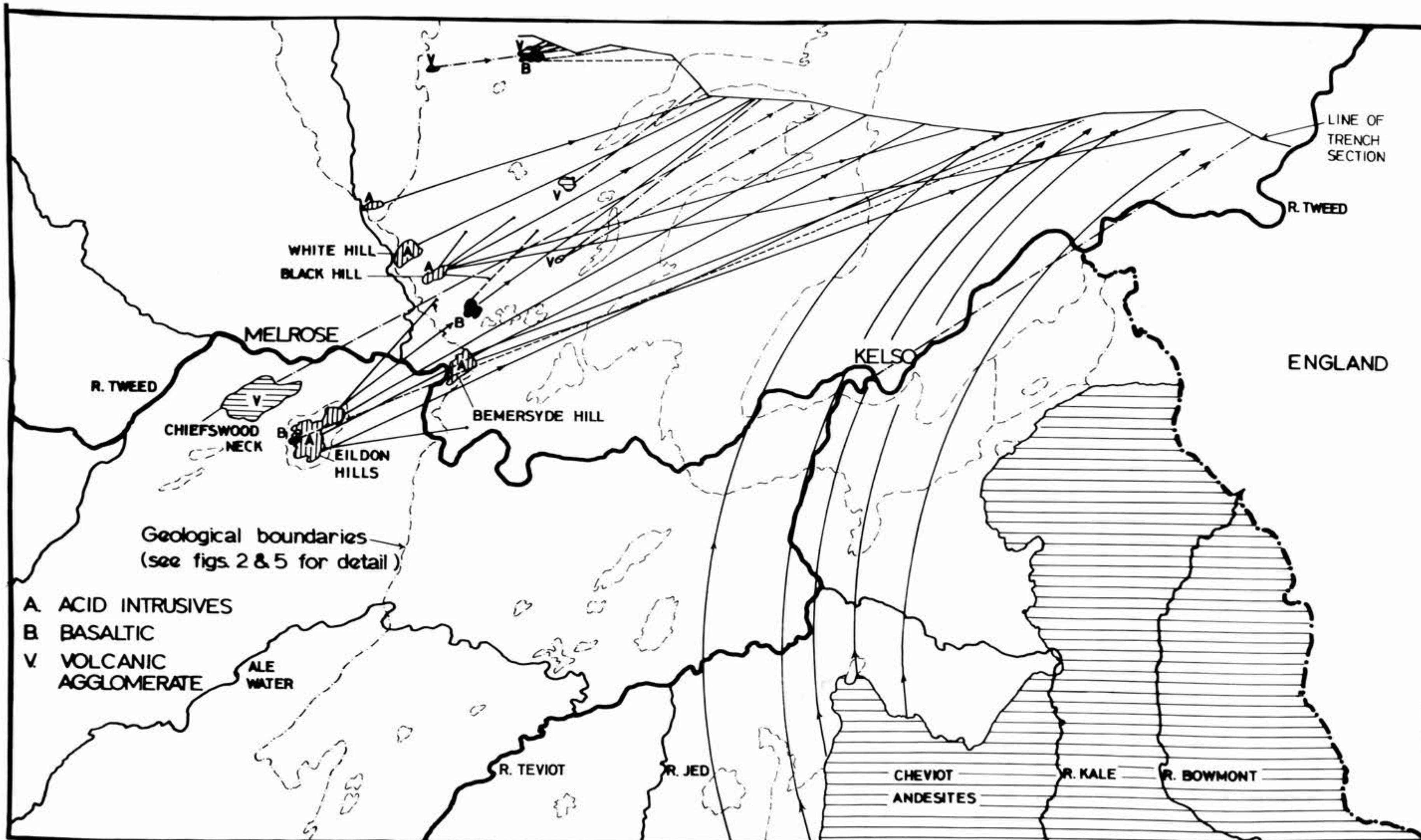


FIG. 22 MOVEMENT OF CERTAIN INDICATOR STONES

CHAPTER FOUR

SECTION ONE: The Surface stone-count series

Introduction and study methods

This chapter is a consideration of several series of stone-counts. These were taken at levels different from the basal trench counts discussed in the previous chapter but related to these in position. The surface counts considered in the early part of this chapter for example were taken as close to the counts from the base of the trench as was allowed by disturbances in stratigraphy made by trenching operations. This was usually within a few metres of a point vertically above the base sample and never more than 10 m from it. Numbers given to samples in the different series are directly relatable. The prefix S. refers to a trench base sample and the prefix S.S. to surface samples.

One hundred stones were taken at each surface site. In many cases particularly on ploughed or recently planted land collection was based on a 2 m square quadrat set out by string and pegs on the surface. Where digging was necessary to remove a vegetation cover a one metre square quadrat was used. These stones were usually collected in a horizon of about 10-20 cm. Since the two methods differed slightly checks were made to test the results obtained by each. These are discussed later.

The size of the individual stones taken for study was similar to that used in the trench base counts but in this case stones were not actually seived but size was chosen by inspection, the prime criterion being their handleability for later study. A hand lens was used in identification of some stones. No study of weight was made in this case although subjective observations were made at every site where trends were discernible. The net result when comparing weight to numbers was again to note an increased dominance of the Silurian erratics over the Carboniferous bedrock area in particular. No patterns were particularly clear in the other erratic groups in terms of this comparison although fragments from the sedimentary rock groups tended to be smaller except in some sections very close to bedrock. The basalts appeared about average although their size varied greatly in many samples. The other groups generally appeared to decline in importance in terms of proportions by weight although exceptions were found, particularly in the case of some quartz fragments which reached sizeable proportions over the Carboniferous area in particular.

The reliability of the method

Reliability was considered in two ways. Initially two sites were examined to test the consistency and reliability of the sample obtained One site was located on the relatively flat drumlinised area east of Eccles village (N.T. 770420, site of sample S.S.18) and the other was located low in an inter-drumlin depression a few km to the east (N.T. 826414, site of sample S.S.8). A series of two metre quadrats was set up in these areas as illustrated in Fig. 23 and 100 stones collected from each quadrat. These were then classified according to the groupings outlined in chapter three and the results are shown in Fig. 24. The results show a very high comparability within a permitted sample error limit and this is illustrated by some simple statistics. The sampling error can be calculated for each erratic group at each site by regarding the whole sample as a series of binomial distributions e.g. Standard error = square root of $\frac{P\%\ q\%}{n}$ where p = percentage of any one erratic group, q = % age of remaining groups (100-p) and n = the number of stones per sample, in this case 100. At the 95% probability level the 'true' percentage varies by two standard errors. As a basis

FIG 23 SITE DETAILS : SAMPLING TESTS

SITE 1. M.R. NT 770420
Samples S.S. 18a - 18d.

SITE 2. M.R. NT 826414
Samples S.S. 8a - 8d.

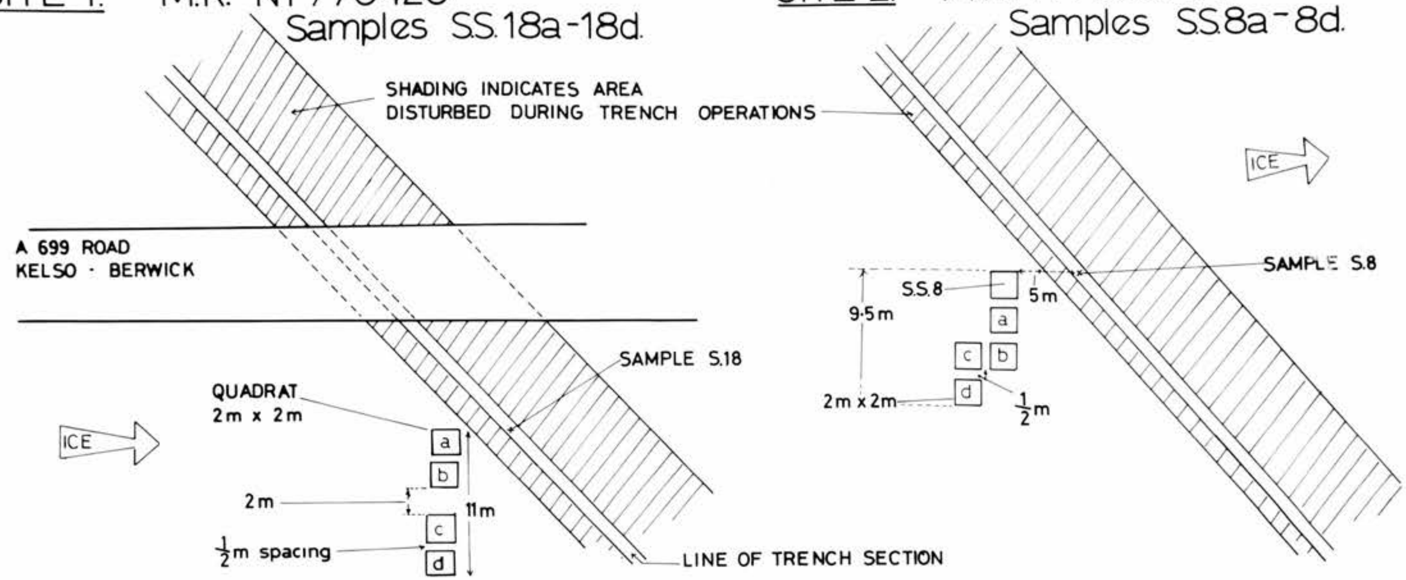
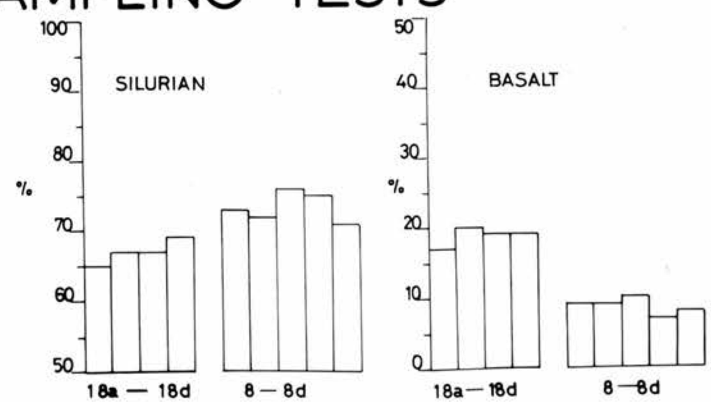


FIG. 24 RESULTS OF SAMPLING TESTS

	18a	b	c	d	8	8a	b	c	d
SILURIAN	65	67	67	69	73	72	76	75	71
BASALT	17	20	19	19	9	9	10	7	8
CARBONIFEROUS	1	4	1	3	4	3	3	5	3
VEIN ROCK	5	1	5	3	5	4	6	3	5
AGGLOMERATE	2	2	1	0	1	1	0	1	0
OTHER IGNEOUS	3	1	1	1	1	0	0	2	1
TRACHYTE	1	0	1	0	0	1	0	0	1
ANDESITE	0	1	0	0	0	1	0	1	0
OLD RED S'STONE	0	1	1	2	0	0	0	0	0
OTHERS	6	3	4	3	7	9	5	6	5



for calculation in this instance the mean percentage, for each erratic group at each of the two sites was taken as 'p'. The results were as follows.

Site 1

Silurian mean (p) = 67

$\therefore$ q = 33

n = 100

$\therefore$ Standard error = square root of $\frac{67 \times 33}{100}$ = 4.70

Basalt	(mean-p = 18.75)	S.E. = 3.90
Carboniferous	(mean-p = 2.25)	S.E. = 1.48
Vein Rocks	(mean-p = 3.50)	S.E. = 1.84
Agglomerate	(mean-p = 1.25)	S.E. = 1.11
Other igneous	(mean-p = 1.50)	S.E. = 1.22
Trachyte	(mean-p = 0.50)	S.E. = 0,71
Andesite	(mean-p = 0.50)	S.E. = 0.71
O.R.S.	(mean-p = 1.00)	S.E. = 1.00
Others	(mean-p = 4.00)	S.E. = 1.96

$\therefore$ "True" percentage at the 95% level is as follows.

Silurian	= 67	±	(2x4.70)	= Range 57.6% - 76.4%
Basalt	= 18.75	±	(2x3.90)	= Range 11.0% - 26.5%
Carboniferous	= 2.25	±	(2x1.48)	= Range 0% - 5.2%
Vein Rocks	= 3.50	±	(2x1.84)	= Range 0% - 7.2%
Agglomerate	= 1.25	±	(2x1.11)	= Range 0% - 3.5%
Other igneous	= 1.50	±	(2x1.22)	= Range 0% - 3.9%
Trachyte	= 0.50	±	(2x0.71)	= Range 0% - 1.9%
Andesite	= 0.50	±	(2x0.71)	= Range 0% - 1.9%
Old Red Sandstone	= 1.00	±	(2x1.00)	= Range 0% - 3.0%
Others	= 4.00	±	(2x1.96)	= Range 0.1% - 7.9%

Site 2

Similarly at Site 2, the 'true' percentages of the suites at the 95% level is as follows.

Silurian	= 74.6	±	(2x4.35)	= Range 65.9% - 83.3%
Basalt	= 8.6	±	(2x2.80)	= Range 3.0% - 14.2%
Vein Rocks	= 4.6	±	(2x2.09)	= Range 0.4% - 8.8%
Carboniferous	= 3.6	±	(2x1.86)	= Range 0% - 7.3%
Other igneous	= 0.8	±	(2x0.89)	= Range 0% - 2.6%
Vent types	= 0.6	±	(2x0.77)	= Range 0% - 2.1%
Trachyte-Felsite	= 0.4	±	(2x0.63)	= Range 0% - 1.7%
Andesite	= 0.4	±	(2x0.63)	= Range 0% - 1.7%
Others	= 6.4	±	(2x2.45)	= Range 1.5%- 11.3%

The consistency of results at each site (Fig. 24) and their concentration generally well within permitted statistical limits appears to confirm both the reliability of the method and the consistency of till composition locally. This suggests that samples taken by this method are indeed meaningful representations of the till in any particular area.

A second series of studies was carried out at six sites to compare the two methods of sample collection that were outlined previously, one based on a two metre surface quadrat and the other on a one metre quadrat. Fig. 25 illustrates the similarity in results achieved by each method. Variation at each site is no greater than was found in Fig. 24, the latter representing samples taken from one site by one method. Some slight variation is to be expected by the very fact that the results only represent a sample population and there is no need to quote statistical values to draw attention to the low deviation attained by the two techniques as illustrated in Fig. 25. Uniformity is particularly apparent on the Carboniferous area. In practice the two methods were used as field conditions dictated and no discrimination will be made between the two in the presentation of results.

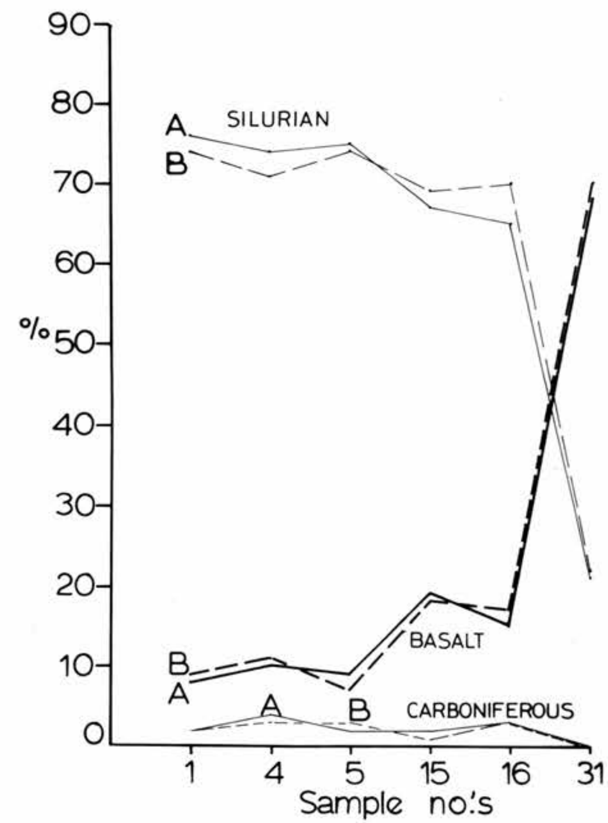
The potential influence of agriculture, particularly ploughing, harrowing or rolling of land, and its influence on surface or near surface samples was closely examined during fieldwork especially as regards the potential break-down of sedimentary rocks. As far as this could be gauged, field experience suggested this to be of minimal effect and for the purposes of this study it could virtually be ignored. During field studies, weathered and broken fragments could often be detected and counted even though they could not be picked out from the till. A more significant impact of agriculture would seem to have been the removal of boulders and larger stones from the fields and their incorporation in drystone dykes or stone piles. This had a less direct effect on the

FIG. 25 A COMPARISON OF RESULTS FROM DIFFERENT METHODS OF SURFACE SAMPLING.

A : SAMPLES FROM '2 METRE' QUADRATS.
B : SAMPLES FROM '1 METRE' QUADRATS.

Sample numbers

	S.S.1		S.S.4		S.S.5		S.S.15		S.S.16		S.S.31	
	A	B	A	B	A	B	A	B	A	B	A	B
SILURIAN	76	74	74	71	75	74	67	69	65	70	21	22
BASALT	8	9	10	11	9	7	19	18	15	17	68	70
VEIN ROCKS	7	5	3	5	4	5	4	5	5	3	2	0
CARBONIF'S.	2	2	4	3	2	3	2	1	3	3	0	0
AGGLOM. etc.	2	2	1	0	3	2	1	1	2	1	0	1
OTHER IGN.	0	1	0	0	1	0	0	0	0	0	0	0
TRACHYTE	0	0	1	1	0	0	1	0	1	1	2	2
ANDESITE	0	0	0	1	2	0	0	0	0	0	0	0
OLD RED S'ST.	0	0	0	0	1	1	1	0	2	1	4	3
OTHERS	5	7	7	8	4	8	5	6	7	4	3	2



studies concerned in this instance however.

The results of the surface stone-count sequence

Fig. 26 illustrates the composite pattern of results from this series of surface stone counts. (The scale and points of reference are as used in Fig. 19 relating in that instance to the stone counts from the trench base.) An examination of the results shown in Fig. 26 is best approached on an areal basis.

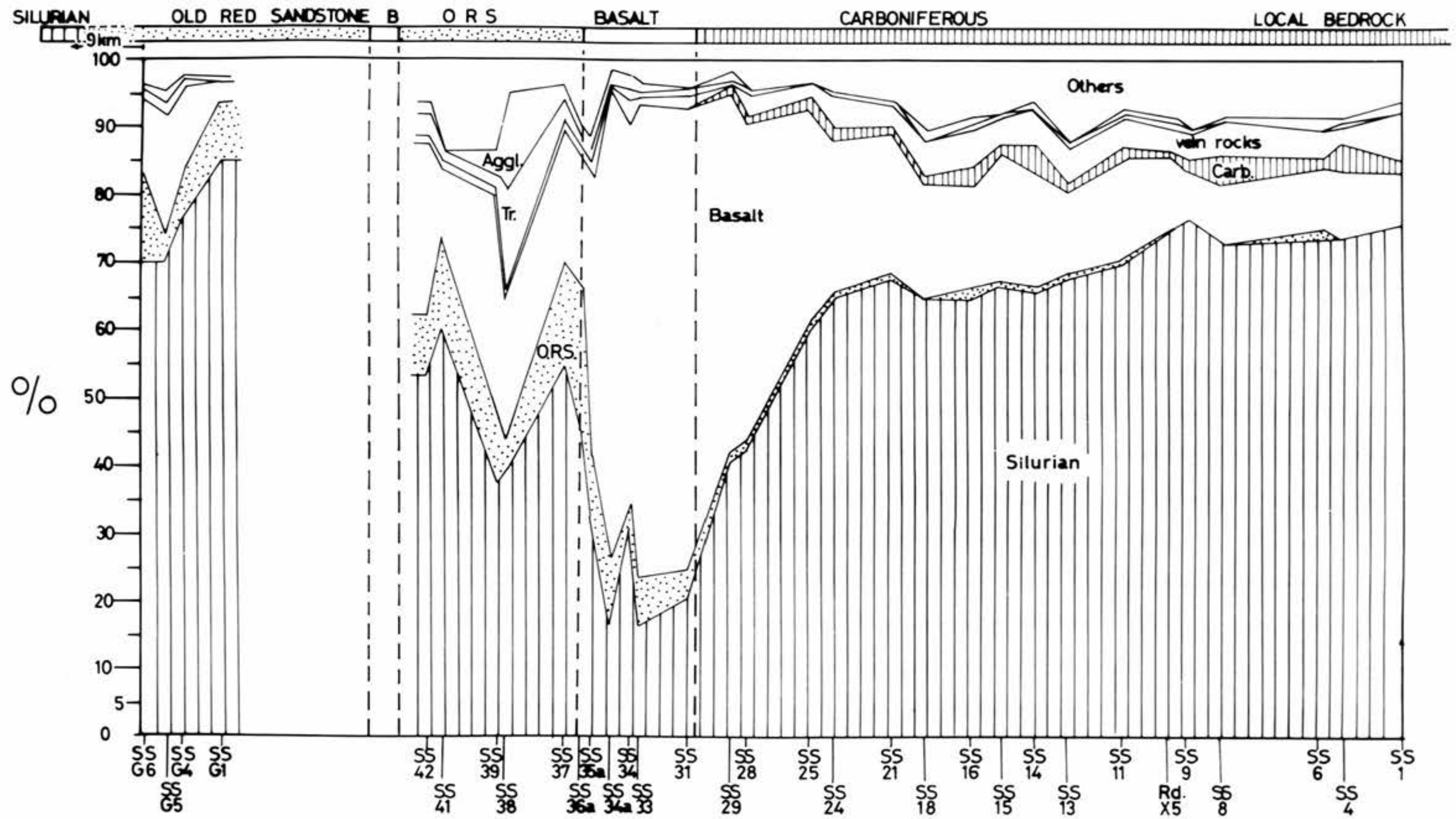
The Old Red Sandstone area The dominance of Silurian erratics in these surface counts is immediately apparent over the Old Red area. Silurian erratics reach concentrations of over 85% in some cases and only at one site was a count of less than 40% recorded. (It has already been suggested that many greywacke erratics classified in this instance as Silurian could possibly have been derived from the conglomerates of Old Red Sandstone age found in Lauderdale. No means of testing this hypothesis was found although in this instance, where surface counts are concerned the problem is perhaps a lesser one since the erratics nearer the surface of the tills are suggested as being derived from deeper in the ice and hence from farther afield in the Silurian area.) Old Red Sandstone erratics rarely reach concentrations of even 20% and frequently are 10% or less. The lowest counts were noted on parts of the tail of Knock Hill in the north-west of the study area with a small but steady increase eastwards to the edge of the Old Red area.

Basalt counts also varied somewhat although tending to exceed concentrations of Old Red at most sites examined. A maximum count of 17% basalt was recorded on the tail of Knock Hill (S.S.G5) although a count of only 3% basalt was also recorded on the other flank of this extensive tail. Basalt concentrations rise to over 20% at surface sites on the low ground down-ice of the East Gordon ridge, the latter, part of the Kelso Traps.

FIG. 26

COMPOSITION OF THE SURFACE TILL

Erratics in % numbers



SURFACE SAMPLES (SS SERIES)

Sample sites correspond with similarly numbered samples from the basal (s) series (fig.19)

The remainder of the till on the surface of the Old Red area is made up of varying quantities of volcanic agglomerate, rocks of the trachyte-felsite groups, some quartz fragments and a few generally small unrecognised erratics. Small amounts of agglomerate (1-4%) are found over much of the Old Red study area with one notably high count in S.S.38 (11.3%). This high count appears to correspond with a high of 11% agglomerate noted a short distance obliquely up-ice at S.39 in the basal stone-count series. (The surface count at site 39 only showed 4% agglomerate and the basal count at site 38 only 2%.) The locally high concentrations of this type of rock have already been suggested as indicating the prescence of some small pipe or vent at a short distance up-ice of the site of S.39. The lack of any quantity of agglomerate with distance is due to its low resistance to erosion as well as to rapid dilution.

Rocks classified in the trachyte-felsite group were not found in the west of the Old Red area towards Knock Hill. Along the line of the trench section they did not appear as surface erratics until the southern flanks of the East Gordon ridge were reached. Concentrations in the depression east of this are generally under 5% although reaching 13% in an abnormally high count in S.S.38. The reason for this maximum is not readily apparent.

<u>The Basalt area</u> Moving away from the Old Red onto the higher ground of the Kelso Lavas, an immediate sharp rise in surface concentrations of basalt is noted. This attains a maximum of 70% on and just down-ice of the higher parts of the basalt area. As the downstream limits of the basalt bedrock area are reached, counts of basalt have fallen to about 50% on the surface of these slightly deeper tills. This fall is accompanied by a rise in the Silurian count from under 20% to over 40% over this distance.

Counts of Old Red Sandstone erratics diminish fairly rapidly once off the Old Red bedrock area. They are generally under 10% over most of the basalt in this area and have fallen consistently to under 5% towards the down-ice limits of the basalt bedrock.

Small quantities of vein rocks (mainly varieties of quartz), trachyte, volcanic agglomerate and "other" rocks make up the remainder of these often thin tills on the basalt area, never collectively reaching as much as 10% of the stone count at any of the sites examined. The basalt fragments, which formed the main component of the till, tended to be angular to sub-angular in appearance for the most part and exhibited considerable variety in size. Silurian erratics were characteristically rounded in appearance and dominated by greywackes. While never attaining anything like boulder dimensions, many of the Silurian stones were consistently over c. 10 cm a-axis except on some of the very high areas where they tended to be smaller and more scarce. Old Red Sandstone erratics tended generally to be fairly small fragments of red or pink sandstones although occasional larger fragments were found.

The Carboniferous area Off the basalt area onto the area underlain by Carboniferous bedrock the basalt counts initially fall away sharply but farther east this fall evens off somewhat. From the 50% concentrations on the down-ice edge of the basalt area a decline is noted to about 10% concentration some 13 km into the Carboniferous area along the pipeline section. This figure of 13 km is misleading to some degree however in that the trench section did not run parallel to former ice movement over the Carboniferous area and also in the fact that the basalt outcrop is irregular in plan (Fig. 2). The eastwards fall off in the basalt count is accompanied by a corresponding rise in Silurian concentrations. From the order of 40% or more on the basalt-Carboniferous junction, Silurian counts rise to 75% and more at the downstream limit of the study area. This increasing dominance of Silurian erratics into the Carboniferous area appeared at times to be even more marked in terms of percentage weight or volume of stones since Silurian erratics clearly dominated other erratic groups in terms of overall stone sizes.

Counts of Carboniferous erratics on the other hand were consistently 5% or less in this series of surface counts and at most sites were lower even than the counts of vein rocks, mostly varieties of quartz. The latter often reached counts of over 5%. Carboniferous erratics tended to be mainly sandstones although shales were also quite frequent. The remainder of the till was made up of variable though generally small amounts of the acid rocks of the trachyte group, volcanic agglomerate and a few smaller unrecognised erratics. Andesite erratics derived from the Cheviot lavas appeared in small numbers towards the east of the study area.

SECTION II A comparison between surface stone-counts and those from the trench base

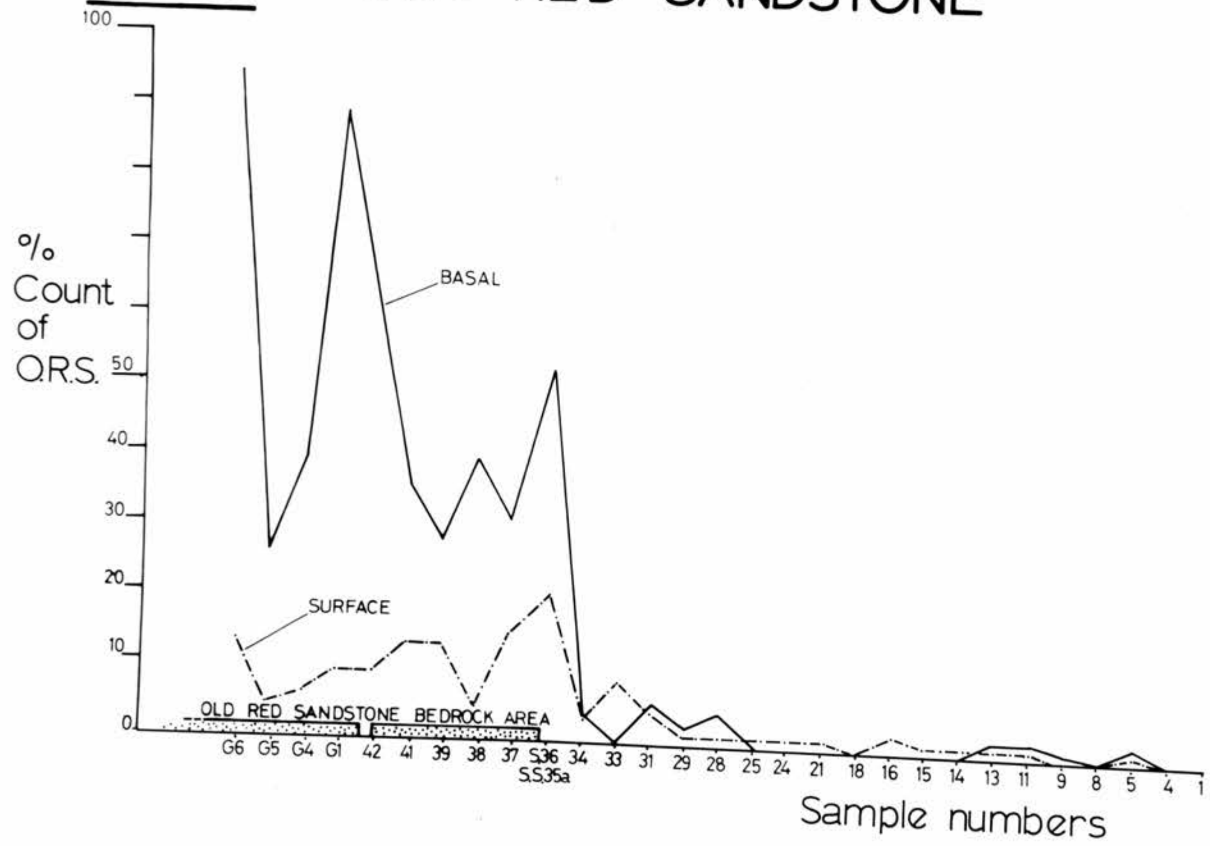
This comparison is best achieved by considering one at a time the behaviour of the different erratic groups over the various parts of the study area in which they are found. Figs. 27 to 30 accordingly show comparisons between the basal and surface counts of the main erratic groups.

The Old Red Sandstone erratics The Old Red erratics show dramatic differences between trench-base and surface counts within the Old Red bedrock area (Fig.27). Particularly striking are the differences exhibited in samples at sites G4 and G6 where differences in the Old Red count of the order of 80% were recorded between surface and trench-base counts. This change occurs over a depth of some 2-2.5 m and basal samples were taken at one metre or less above, Old Red rockhead. In other samples recorded over the Old Red area differences in the two series of counts ranged from about 14% to just over 55% at any one site.
When differences between surface and trench-base were smaller, tills were generally deeper and overall values generally lower throughout the section. In the case of site 39 for example where a difference of only 14% was

FIGS. 27 - 30 incl.

A comparison between surface and basal counts of the main erratic groups.

FIG. 27 OLD RED SANDSTONE



recorded the basal count of Old Red was only some 28%. Similarly in samples at site G.5 the basal count of Old Red reached only 26% and the surface count only 4%.

Overall figures indicate a very rapid fall in Old Red Sandstone counts in till with increasing distance (vertically and horizontally) from bedrock. Differences between the different levels are on the whole less marked in the east of the Old Red study area (sites 35 to 41) and two possible explanations are suggested for this. Initially tills are deeper over parts of this area and the Old Red counts in the basal series itself only rarely exceed 50%. The significance of this appears to be that initially (i.e. in the first two metres or so above bedrock), the Old Red counts fall off very quickly but that this fall appears to stabilise at higher levels, particularly in the east of the study area. It is also likely that by the time the down-ice limits of the Old Red Sandstone area were reached some Old Red erratics would have been moved up along shear planes into higher levels in the basal ice and during subsequent deposition may be expected to be found in greater concentrations at higher levels in the till sheet. Sites 35 to 41 for example lie some 10-15 km down-ice of the western limit of the Old Red area. Samples at G1 and G6 on the other hand lie only some 4 to 5 km from the boundary of the main Old Red group with the conglomerates of Lauderdale (Fig.2).

One major factor in this rapid fall in Old Red concentrations with depth to bedrock however is still the susceptibility of the Old Red Sandstone erratics, most of which are sandstones, to the abrasion process during glacial transport. This is confirmed by several lines of evidence.

(i) The extensive destruction of the Old Red mass in the "intermediate till zone" (referred to in chapter two), between bedrock and the overlying till of mixed origins is one indicator of this weakness. The often considerable amount of sandy material in this layer is indicative of considerable break-down of the Old Red material over very short distances.

(ii) The often extremely fragile nature of many of the Old Red erratics found in till samples as was suggested in the consideration of stone-counts in Chapter three, is also a factor of some significance. This is also reflected in the general lack of sizable Old Red erratics at higher levels in the tills even in the east of the Old Red area or down-ice of it (Fig. 27).

(iii) Ragg et al. (1960) pointed out an important factor when they recognised the weak cementation of the sandstones of the Old Red Sandstone series. These sandstones are by far the major erratics of the Old Red area and few shales or other finer rocks of this series survive at all as erratics.

(iv) A further indicator lies in the apparently rapid reaction of the till matrix over the Old Red area to the proximity of Old Red Sandstone bedrock. In this the sandy nature of the till matrix in areas close to bedrock, is seen as indicative of the rapid breakdown of the local rock.

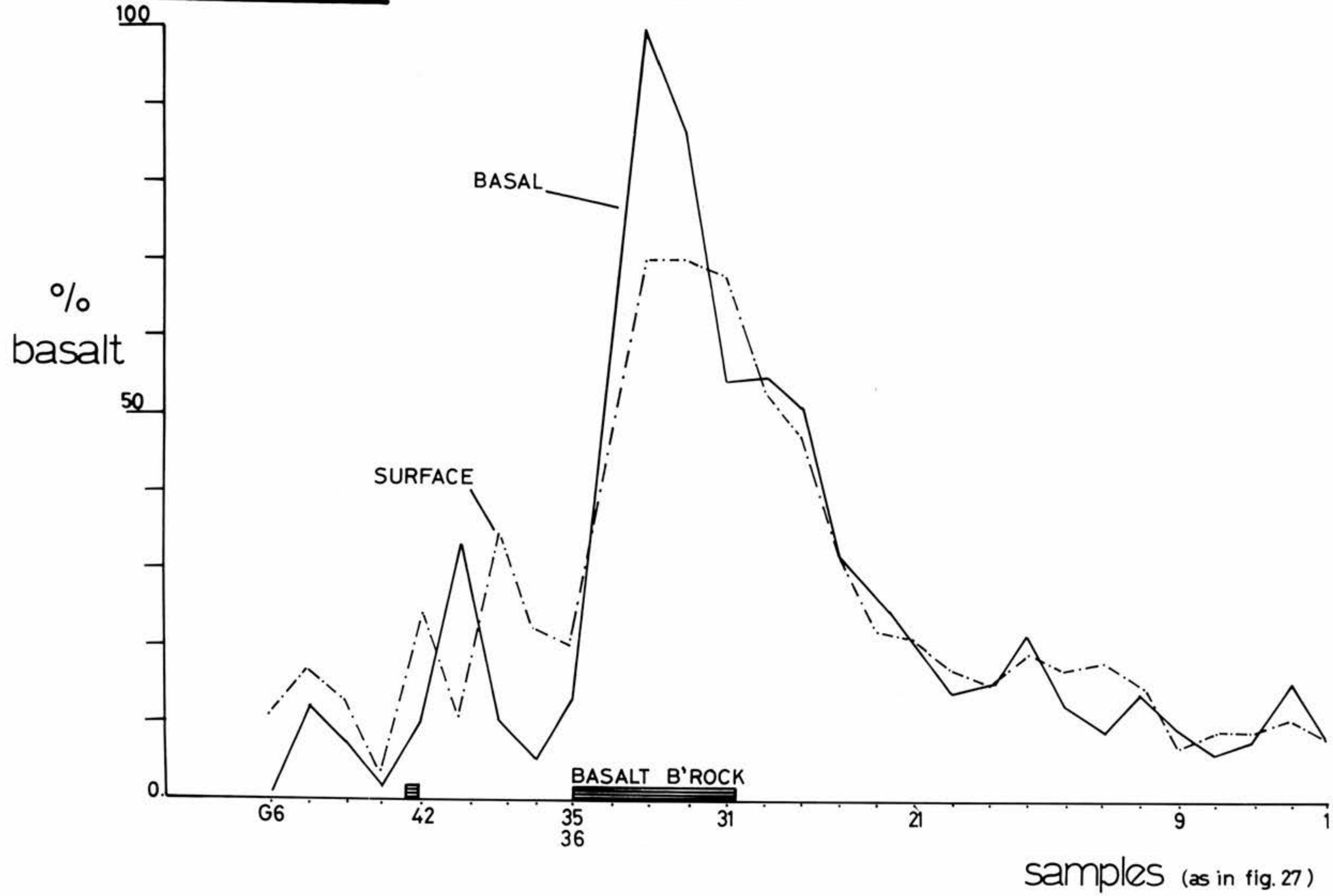
(v) The often coarse nature of the matrix is potentially a factor allowing considerable post-glacial in situ weathering of the sandstone fragments and thus contributing to their low counts in the till.

It is not possible to attempt to quote any figures of average percentage concentration variation in Old Red erratics with depth from bedrock as too many variables are involved. The extent of Old Red bedrock up-ice of any site, particularly where till is more than 2 to 3m deep has been suggested as a factor for example. Variability has also been suggested in terms of intensity of ice action at any site, (as was examined in chapter two in relation to the development of the "intermediate till zone" of near 100% Old Red counts). This question of position appears to have some effect on the destruction of the Old Red bedrock and erratics. In addition there are relatively few areas of deeper tills in which depth to bedrock is known and observations are thus incomplete. In the east of the Old Red area in particular however, it seems that the initially rapid decline in Old Red counts in the first two metres or so above bedrock begins to even out with increasing depth of till.

Old Red erratics in both surface and trench base counts fall off fairly rapidly east of the Old Red area, particularly in the case of the basal counts. Counts of Old Red are under 5% in both series of counts over both the basalt and Carboniferous areas. Old Red erratics appear to be slightly more ubiquitous in surface counts over the Carboniferous area and rather more sporadic in counts at depth. The amounts involved (only about 1% in some surface counts) are so small however that this may not be significant within the reliability of the sampling techniques involved in each.

<u>The basalt erratics</u> Differences between surface and trench base counts of basalt erratics are neither as great, nor as consistently greater in one series or another , as was the case in the counts of Old Red erratics. Some trends are evident however, especially on the main area of basalt bedrock itself. Trench base counts in this area were frequently of the order of 100% basalt in the "intermediate zone" on the higher parts of the ridge where locally the trench was often cut or blasted through solid or broken bedrock (chapter two). Surface counts of basalt in these higher areas reach a maximum of 70% and this contrasts sharply with the much lower figures noted previously in the examination of surface Old Red erratics. Two factors are important in this. Firstly the tills on the highest basalt areas are even thinner than those examined on the Old Red part of the study area. Rather than being about 2 m in depth at their minimum they are often nearer 1 m or less. Bedrock influence is accordingly greater. Secondly the basalt erratics can reasonably be

FIG. 28 BASALT



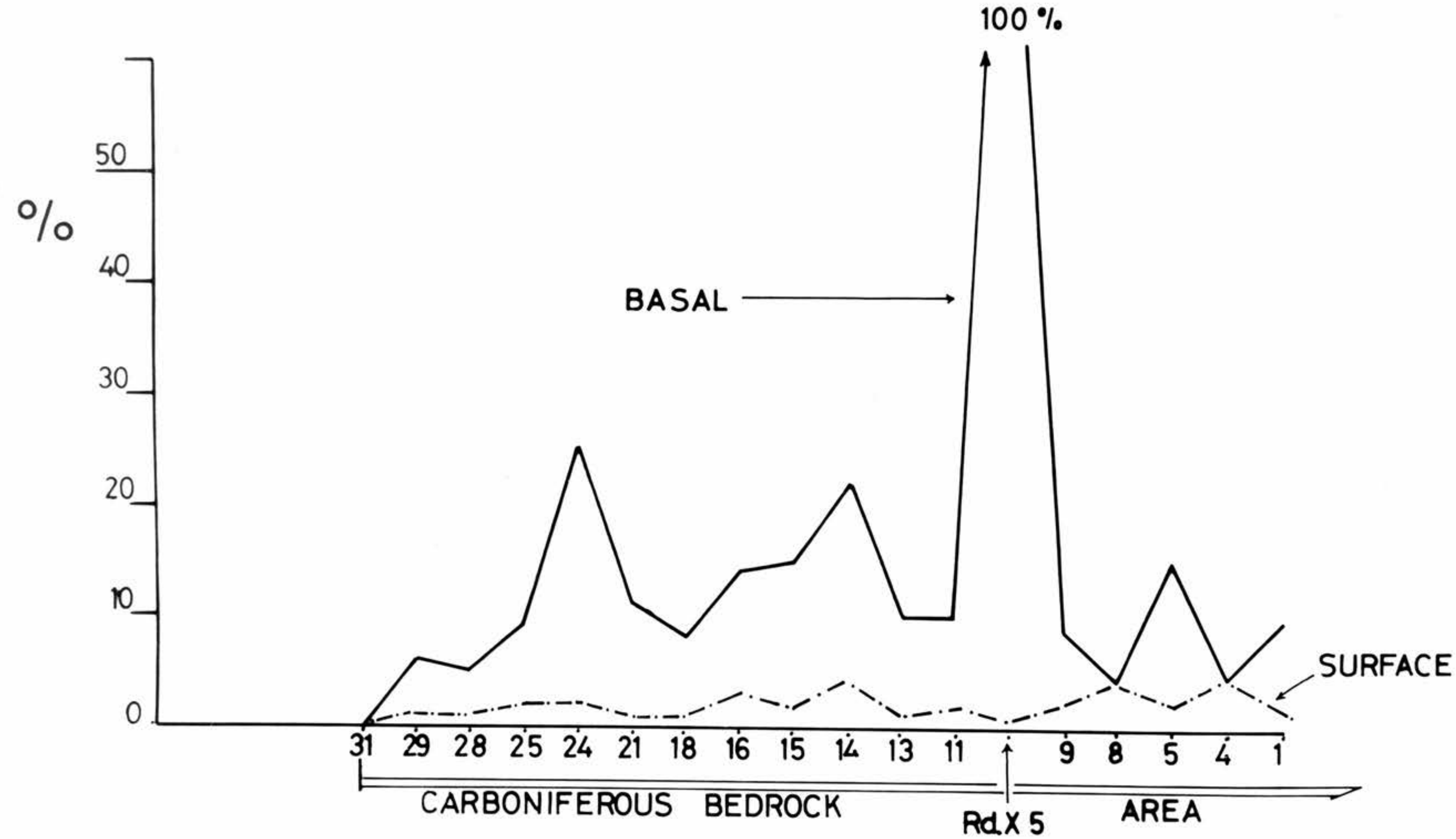
assumed to be much more resistant to abrasion in the glacial environment and survive at levels well away from bedrock. They do tend to fracture considerably as is shown by the variety of angular fragments to be found in the "intermediate till zone" between bedrock and mixed till. On the other hand the less well-developed matrix of this zone, a gritty material of often limited amount, contrasts with the great extent of sandy matrix developed within the same zone in the Old Red tills. This suggests a relative resistance to abrasion by the basalt erratics.

This greater resistance is seen in the survival of the basalt erratics in significant quantities in both surface and trench-base counts over the Carboniferous area to the east of the basalt bedrock. The fall off in basalt concentrations is initially quite marked in both series of counts, falling by about 30% over the first two or three km east of the basalt rocks. This evens out a little on farther progress eastwards and drops to the region of 10% by the eastern limit of the study area. The possibility of some influence from the arm of the lavas running north-east from Kelso on the south side of the Tweed has already been suggested for the basal samples in the Coldstream area (chapter three). Over the Carboniferous area little significant difference appears to exist between the counts from the two different series. Results suggest that basalts are distributed fairly consistently at all levels in the tills down-ice of the basalt bedrock area. This is examined more fully later.

Up-ice of the Kelso Traps, the main basalt body, there are two main basalt sources which impinge more or less directly on the pipeline section. These are the basalt plug of Knock Hill (M.R. 616441) and the east-west running arm of the Kelso lavas referred to as the East Gordon ridge. Differences between surface and trench-base counts of basalts over this Old Red area are nowhere very great, reaching a maximum of just over 20%. It is perhaps significant that in only one site is the trench-base count higher than the surface count. This site (41) lies immediately down-ice of the basalt in the East Gordon ridge and is explained in terms of the greater influence of local basalt bedrock at lower levels. At all other sites surface counts were greater than those at the base of the trench, even on the tail of Knock Hill, though these differences are nowhere very great. This superiority in the surface counts is perhaps explicable to some degree in that surface counts of basalt are inflated by the inability of Old Red erratics to survive to these levels. Trench-base counts of the other hand tend to be much more dominated by the presence of local sandstone rock in the thinner tills, thus effectively depressing any basalts present. The net effect from the two series of counts examined here would appear to be to suggest that absolute basalt contributions are fairly similar at all levels in the deeper tills of the Old Red area except where local bedrock, either Old Red or basalt, tends to have a more direct influence. In many cases there was definitely a real lack of basalt erratics at the base of the trench however. This was noted in samples such as G6 and G1 where Old Red bedrock was noted locally.

<u>The Carboniferous sedimentary erratics</u> Erratics from this geological group behave in a way very similar to those of like type discussed in the consideration of the Old Red Sandstone area. Over the Carboniferous area generally deeper tills are encountered and accordingly local bedrock influence never reaches the proportions noted so frequently over the Old Red area. For the most part basal counts of Carboniferous rocks are below 20%, indicative of the depth of till (i.e. depth to rockhead) in the Carboniferous area. These erratics form even less than 20% of the stone sample when considered in terms of percentage weight or volume. Surface counts on the other hand rarely reach even as much as 5 or 6% Carboniferous content in the series illustrated in Fig. 29. (In another

FIG. 29 CARBONIFEROUS



study involving surface counts in the Carboniferous, which is discussed in a later chapter, Carboniferous percentages did exceed 20% although more frequently they were in the region of 10% and less.

There are two factors which explain the lack of Carboniferous erratics in surface counts relative to basal counts as well as accounting for the relatively low Carboniferous percentages in many basal counts. Fewer Carboniferous erratics may be expected at these highest levels in the ice where the highest levels of the till sheet have their origins. Initially, this is due to the relative lack of resistance to abrasion of the Carboniferous erratics in relation to the more resistant basalt and Silurian erratics, and their considerable destruction and dilution with distance travelled. Secondly, however, fewer Carboniferous erratics would be expected to be found at these higher levels in the ice even accepting their inherent weakness. This is because the higher tills generally represent debris formerly held quite high in the basal ice and containing greater proportions of erratics from farther west and south-west. There would be movement of Carboniferous debris up into the ice along shear planes but this would not be expected to influence this upper one or two metres of till even to the same extent as in the Old Red Sandstone areafor example. Less local debris might be involved here for two main reasons. Firstly, the considerable cover of lodgement till masking the underlying Carboniferous rocks would act ultimately as a protective cover over much of the area and restrict the supply of fresh Carboniferous erratics. Secondly, much of the Silurian debris by this time could conceivably be concentrated in parallel dirt-bands high in the basal ice layers, and would therefore be less affected by shearing movements right at the base of the ice involving movement of the local erratics. Lesser penetration of the local erratics might also be expected in view of the apparent change in character of the ice over the Carboniferous area as discussed previously; a change to a more depositional character.

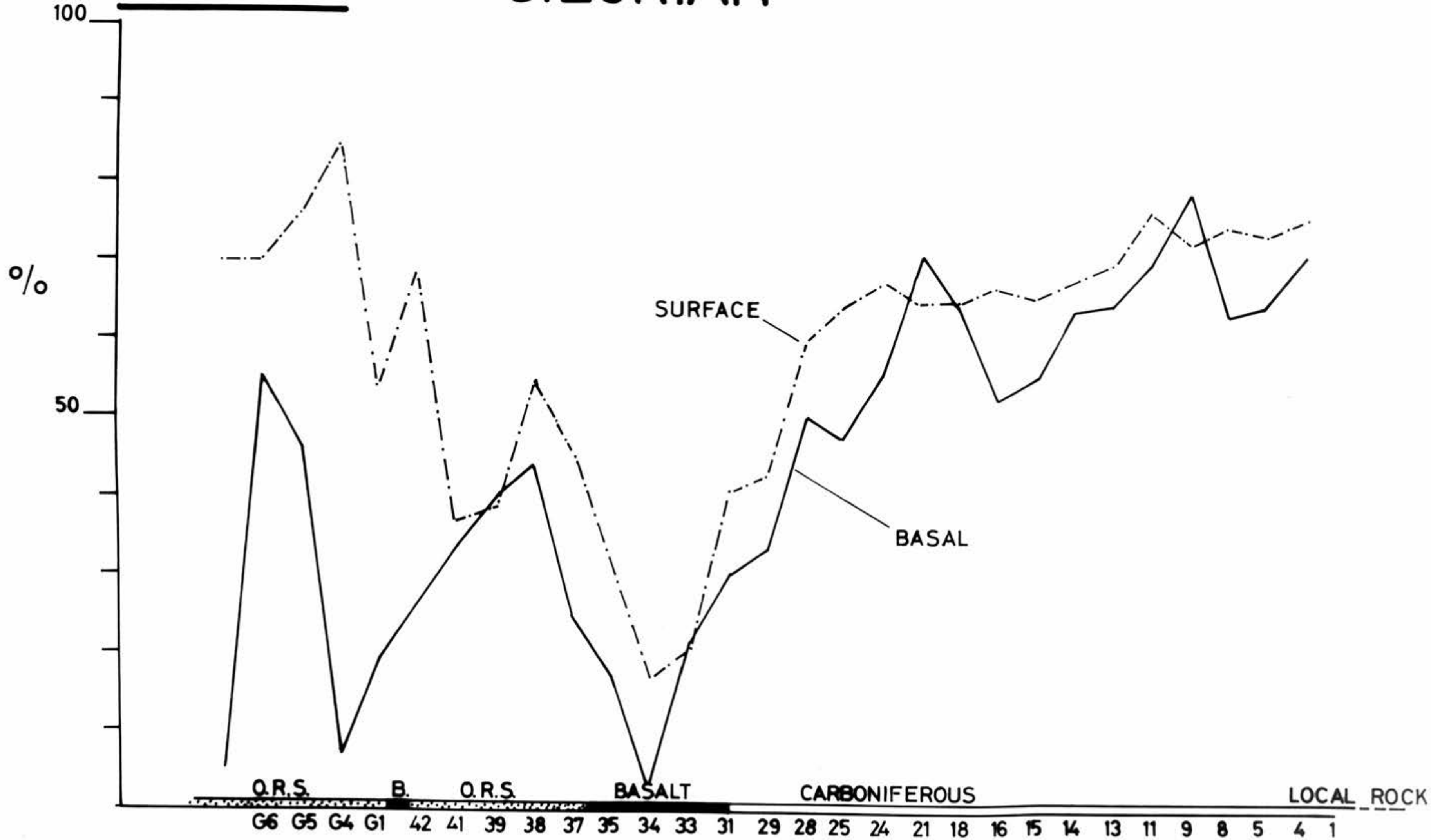
Silurian materials can therefore be expected to dominate these higher levels of englacial material and the following section offers a more comprehensive consideration of this Silurian dominance.

The Silurian erratics Fig. 30 indicates the relationship between the Silurian erratics in the two series of stone counts. It is immediately apparent that in all three geological areas Silurian percentages almost without exception increase towards the surface counts.

In the Old Red Sandstone bedrock area some very dramatic differences exist. Samples G.1 and G.6 for example rise from 7% to 85% and from 5% to 70% respectively from basal to surface counts. These two sites are particularly close to Old Red bedrock and very few exotic erratics occur at lower or lower levels. Some of the explanation of the rise in Silurian dominance must therefore be seen as due to the dominance of Old Red at lower levels and subsequent fall off at higher levels. The weakness of the Old Red erratics is not the only factor however. It is probably most applicable in the east of the Old Red area and down-ice of this where greater quantities of Old Red material might have been expected at higher levels in the ice-sheet. Another explanation is also pertinent however.

The 2-3 m till sections at the various sites over the study area must be seen as representing sections through the materials of an ice sheet and its immediate bed at a point in time. This point in time must be when the ice finally ceased forward motion at any particular site. Admittedly some modification may occur after this time, (chapter two) although in the materials being studied in these counts, the consideration is of debris which has largely maintained the composition, structure and relative position it held in or immediately below the ice. In this

FIG. 30 SILURIAN



instance for example, sand lenses showing almost unaltered current-bedded sands have been noted on the complex tail of Knock Hill (chapter two). Following the explanation offered for these in chapter two it will be recognised that the till overlying these (e.g. samples S.S.G4 and S.S.G5) must be material which, but for the cessation of forward motion in the ice sheet, would probably have been carried over the area as englacial debris. This material higher in the ice would have its origins much farther west for the most part, into the conglomerates of Lauderdale and more particularly the great Silurian mass beyond. This must be the major explanation of the high Silurian percentages at these higher levels in the till. The essentially lodgement nature of the appearance of these surface, and essentially ablation, tills has already been suggested (chapter two). This is not to suggest that all surface tills were deposited under these stagnant ice conditions however. In many cases no upper till divisions could be detected and it is possible that in many areas the high surface Silurian counts could still result from deposition of higher englacial material under a moving although a slowing and dying ice sheet. Small sand or fine gravel lenses do not necessarily indicate stagnant ice but rather an abundance of water at that particular depositional stage. It is equally possible however that melt out of till under stagnant ice could result without evidence in the section exposed by trenching operations examined here. Attention has already been drawn in chapter two to the occurrence of small isolated lenses of grit or sand in till sections which may be indicative of some final squeeze melt.

Off the Old Red Sandstone area and onto the area of basalt bedrock to the east, lower Silurian percentages are recorded generally at all levels in the section and particularly on the higher parts of the basalt area. The great importance of basalts at all levels in these thinner tills is especially important in producing this effect. In many basal counts high on the basalt area, very few Silurian erratics were recorded and such as were found were generally quite small. In sample S.33 for example only 3% Silurian was recorded and this contributed only 0.4% of the sample by weight or volume. In other localities 100% basalt was recorded. Silurian influence in these areas was often restricted to less than one metre below the surface. As in the Old Red area this higher material is largely seen as debris released from within the ice at a very late stage in glaciation as the ice finally slowed down. Again the section on these high basalt areas can be thought of as representing the picture of an ice sheet and its immediate bed at a point in time. The relative lack of Silurian material even in many surface counts over parts of the basalt area is particularly interesting in view of the great depths of material, dominated by Silurian erratics, found over the Carboniferous area to the east. It would seem to have particular significance from the point of view of understanding the deposition of this material in the Carboniferous area, particularly the period of deposition involved as well as the mode of deposition. This will be discussed more fully in a later chapter particularly when such relevant material as the fabric analyses have been considered.

Moving onto the lee of the main lava body and eastwards onto the Carboniferous area, Silurian percentages in both series of counts rise appreciably although still showing higher values in the surface counts. This could be partially explicable in terms of a fall in Carboniferous erratics at higher levels due to their lack of resistance to erosion but this is not the main factor. A fairly consistent count of basalts has already been noted in surface counts suggesting that higher counts of Carboniferous erratics might have been expected at the surface even if only in the east of the study area. Although surface counts do increase slightly in the east of the area they remain at low levels and below the levels of the basal series. The explanation of this lies only partly in the tend~~a~~ncy of the Carboniferous erratics to erode easily and only partly in the depth of till overlying bedrock in the area. It must also be the case that this surface material was the last to be deposited and that its origins were probably high in the basal ice. It must be recognised as being derived from much more exotic sources than tills deeper in and below the section examined. In view of the sands and gravels noted previously as lying underneath this top till in places, its deposition by slow melting out rather than by slow accretion or plastering on is suggested in many instances. Higher Silurian counts are to be expected at higher levels within the ice and accordingly in the final till section, however it is deposited.

SECTION III A study of counts at different levels within the trench

During studies of the continuous pipeline section across the study area several samples were collected at locations other than the base of the trench. Many of these were of adequate size for stone count analysis and stone counts were subsequently carried out on these using the method outlined previously for the basal stone counts. The following section is a consideration of the results from five of these sites at which studies were undertaken. Three sites lie on the Old Red Sanstone bedrock area and the other two lie on the Carboniferous area. All are sites located close to or on local bedrock. They are intended to complete the consideration of the trends noted previously in this chapter. The series of samples examined in section II were 2 m or more apart vertically at any site and the examples studied here are an attempt to examine the variations in till composition at levels in the section between these two levels.

Samples at the five sites examined here had an average stone content of just over 87 stones per sample. Median and mode values were 100. All sections were through the top 2 to 2.5 m of till at any site. In the examination of Figs. 31 to 35 inclusive, small inset diagrams illustrate the direction of the section lines in relation to the direction of the last ice movement. Almost all the sections examined ran obliquely to the direction of this movement and this is an important factor in considering the stone-count patterns derived from them. Occasionally small geological diagrams are also necessary where local geological change had a significant effect on the results.

<u>SITE I</u> Fig. 31 illustrates a site on the tail of Knock Hill in the west of the Old Red Sandstone study area. The base of the section was in a very red sandy till of almost 100% counts of Old Red (the "intermediate till zone") and Old Red bedrock was exposed locally in the trench. A few small greywacke pebbles made up the rest of the basal count. At higher levels in the section stone size appeared to decrease gradually although rising again on the surface. Till colour changed from a very deep red in the base to a darker red-brown nearer the surface. The till also became less sandy in texture compared to lower levels although still showing fairly high sand content.

The Old Red count falls away dramatically from 95% to 6% in less than two metres. Reasons for this have already been discussed. The subsequent slight rise in the surface count of Old Red is more difficult to explain. This may be due in part to the sampling techniques but another possibility does exist. Directly up-ice of this site is the basaltic plug of Knock Hill which rises some 60 m higher than this site. The western face of Knock Hill on the other hand rises some 120 m from the valley floor beyond. Such an obstacle to ice movement must have

FIGS. 31 – 35 incl.

VARIATIONS IN STONE - COUNTS WITH DEPTH TO BEDROCK.

THE GEOLOGICAL AND OTHER SYMBOLISM USED IN FIGS. 32 - 35 IS AS ILLUSTRATED IN FIG. 31.

ALL SECTIONS ARE APPROXIMATELY 2·50m IN VERTICAL EXTENT UNLESS OTHERWISE INDICATED.

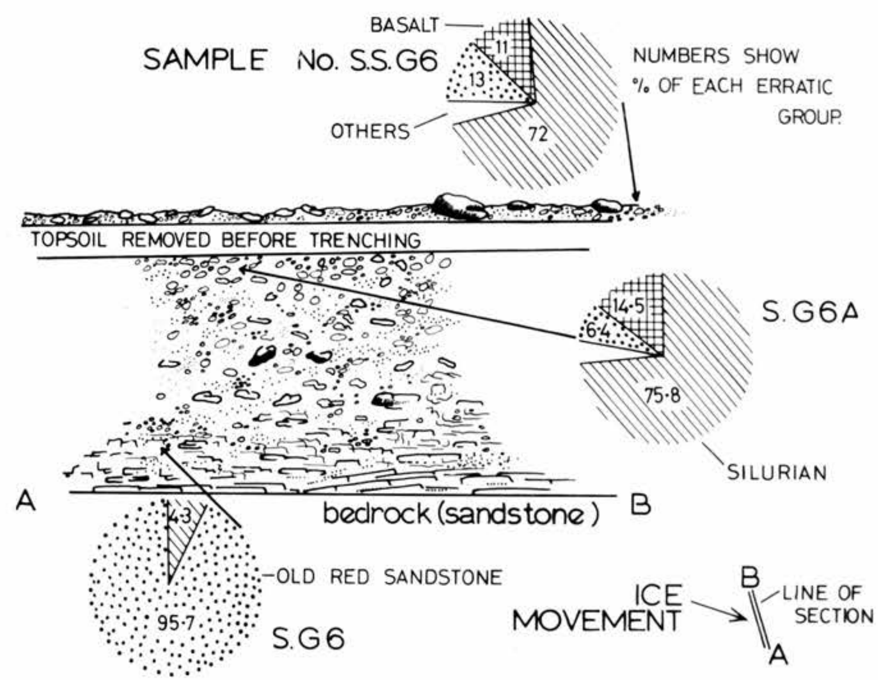


FIG. 31 Old Red Sandstone bedrock area : M.R. NT 622445.
(SITE ON TAIL OF KNOCK HILL)

caused considerable shearing in the basal ice layers and it seems quite possible that quantities of sandstone may have been moved up along shear planes to fairly high levels in the basal ice. Ordinarily these fragments would not survive long in this environment but since the fragments considered here had only travelled a short distance before ice flow slowed and they were deposited, then it is not unreasonable that some may have survived. Some Old Red Sandstone boulders were even found on the surface in this area.

Silurian counts on the other hand are more or less similar in the two upper samples suggesting some uniformity in this upper metre of till. (Absolute amounts of Silurian may really be slightly greater in the surface count but percentages depressed by the relative increase in Old Red content. This is not certain.) Within 1 km of this site but at a similar level on the tail of Knock Hill well defined sand lenses of considerable dimensions have been recorded below this upper metre or more of till. This has been suggested as supporting the hypothesis that this upper metre or so of till in this area was let down from stagnant ice. The variation in the basalt count in the upper two samples is, like the Silurian, small enough to be considered negligible within the reliability of the sampling techniques, varying by only 3%

SITE 2 Fig. 32 offers an even more complete picture of counts at varying levels in a section. This site is located on the flanks of the East Gordon ridge. It is shown as lying on basalt bedrock according to geological survey maps but the trench section exposed Old Red Sandstone bedrock. This section typifies what might be expected in tills of the Old Red area. There are no great complicatory factors such as local relief peculiarities at this site. The only modification is in the influence of the basaltic section of the East Gordon ridge which curves round just up-ice of this site. Its prescence merely serves to

FIGS. 32 & 33. Old Red Sandstone bedrock area.

Fig. 32 M.R. NT 673434

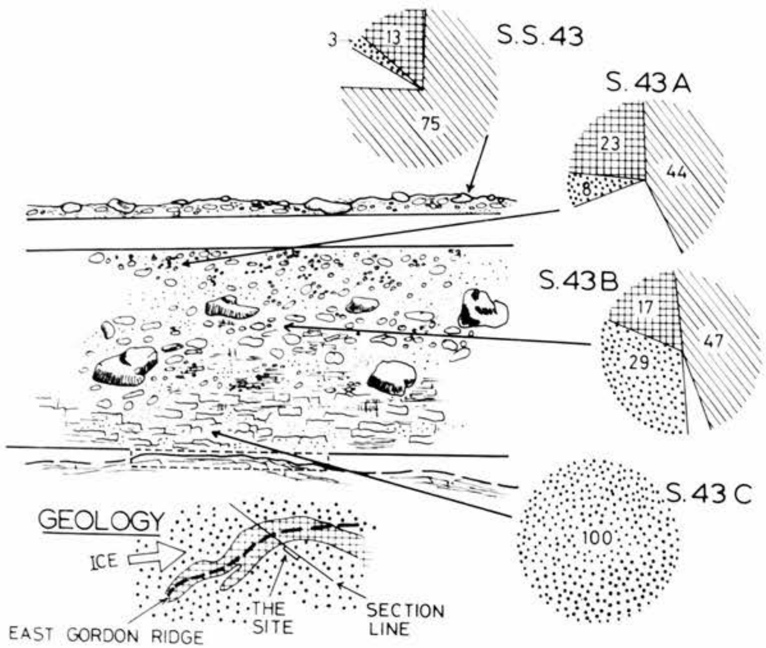
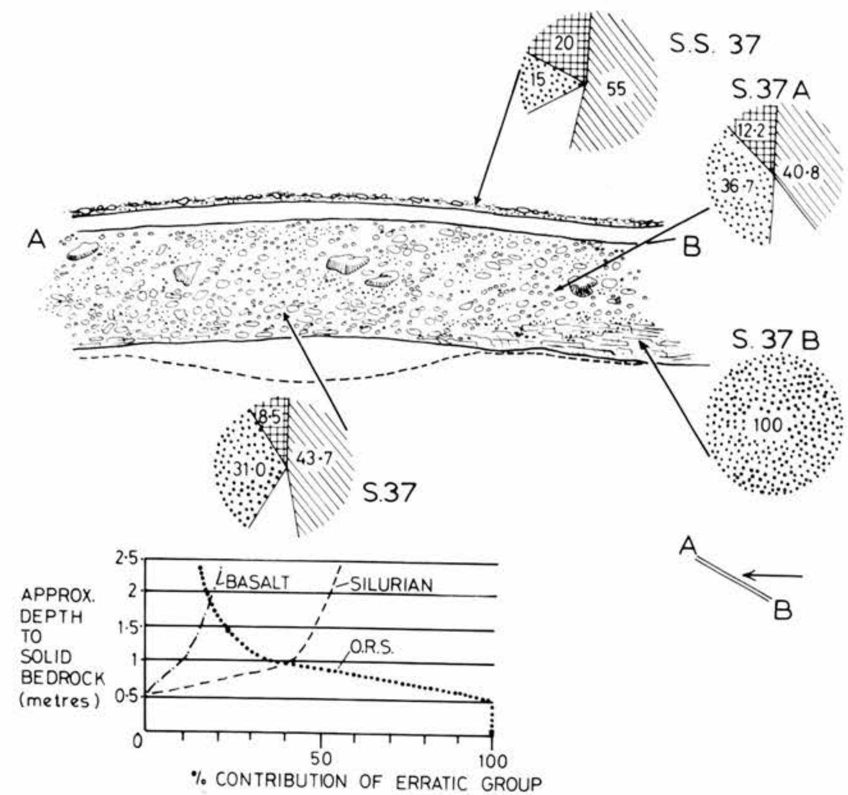


Fig. 33 M.R. NT 693428



illustrate the way in which different levels in the final section may be attributable to different levels in the ice however. The highest levels in the section, derived from the highest debris zones in the ice, show considerable domination by Silurian material culminating in a surface count of some 75%. Old Red counts are down as low as 3% here and basalts only reach 13%. Less than a metre below this Silurian counts have fallen to around 45% and this is held fairly consistently over the middle part of the section. Basalt counts rise to over 20% in this central part due to the maximum influence of the basalt bedrock up-ice. The maximum of 23% is reached in the upper part of this middle section. Above this the basalt erratics have not penetrated in the same strength into the masses of Silurian material. In the central part of the section the Old Red erratics have fallen off rapidly from the high basalt counts. A count of only 29% was recorded at less than a metre from the trench base. Below this level the Old Red erratics become dominant. The material in the trench base is a till but one of 100% Old Red stones. This is the zone referred to as the "intermediate till zone" (chapter two). Typically it consists of fragments of weak sandstone rock in a compact sandy matrix. Occasionally at this site a few small greywacke or occassional basalt fragments were noted within this zone but were too small to be included in the stone count. At its upper limit this zone merges gradually into the overlying mixed till often with patches of each found within the other.

In contemplating the surface dominance of Silurian erratics there is perhaps a possible effect of frost action in moving Silurian stones to the surface, especially considering the size of many surface Silurian erratics. While it is not possible to completely neglect such a possibility, many of the Silurian fragments in the middle part of the section were no larger than the basalt fragments and yet the basalts experience a distinct decline towards the surface. There seems therefore no reason to suppose that the high percentage of Silurian erratics is greatly influenced by movement up from lower levels due to frost action. Such an effect is difficult to gauge however.

SITE 3 Fig. 33 at first glance appears to contradict the general pattern in that sample S. 37 has more Silurian and less Old Red than sample S.37A despite being at a lower level in the trench. This apparent contradiction is explained however if the actual bedrock surface is projected beneath the surface as in Fig. 33. This merely illustrates that position in the section itself is not the significant factor but rather it is position in relation to the bedrock surface.

Fig. 33 then presents much the same pattern as in Fig. 32. Again the section seems divisible into three units and even though these merge into each other the differences between each are quite marked. The lower section, the "intermediate till zone" between bedrock and mixed till is dominated to near 100% concentrations by the local sandstones in both stone counts and in matrix materials. This gives way gradually to a middle zone which is dominated by quantities of Silurian (40-45%) and Old Red Sandstone (30-35%) with secondary concentrations of basalt (c. 10%). Into the upper section Silurian dominance rises to over 50% Basalts have increased to around 20% and the decline in Old Red counts has continued to around 15%. The basalt is mainly derived from the higher ground of part of the East Cordon ridge to the west . The relatively higher surface count of Old Red erratics when compared to such as the surface samples on the tail of Knock Hill for example, may also be due to some influence from the Old Red Sandstone part of this higher ridge area. Equally it may be due in part to the location of this site in the east of the Old Red Sandstone area as a whole (section II, chapter 4). The trends represented graphically in Fig. 33 illustrate the very rapid nature of the initial rise in Silurian counts and fall off in Old Red counts above the "intermediate till zone" near the trench base. Those rates then even off with increasing depth to bedrock at higher levels in the section.

SITE 4 Fig. 34 is the first of the examples illustrated from the Carboniferous bedrock area. It is located on the ridge of green micaceous sandstone lying to the east of Hume village. The site lies about 1 km east of the basalt lavas and this is reflected in the strong basalt influence in the stone counts. From the 100% Carboniferous concentrations in the "intermediate till zone" at the base of the section Carboniferous counts fall off rapidly higher in the sections to reach under 5% at little more than a metre above this area of maximum concentration. By the surface counts this has fallen to 1%. A rapid rise in Silurian and basalt counts accompanies this fall in Carboniferous erratics. Basalts reach their maximum of 51% deeper in the section than the Silurian which characteristically show a maximum (43%) in the surface count. Reasons for this surface maximum have already been fully discussed.

SITE 5 Fig. 35 shows the final example in this series. This site shows deeply brecciated and rotted Carboniferous shales in section. The trends shown by the stone counts are all fairly typical of what has been described above for other sites. It was notable however that of the 24% Carboniferous stone count recorded in the sample Rd.X.5B very few were shales. Most were varieties of sandstone with a green/buff micaceous variety especially prominent. The section of trench illustrated in Fig. 35 continued to show traces of shale bedrock for over 70 m to the west and no evidence of sandstone bedrock was found. This may be a significant factor regarding the origins of the till in the middle part of this section suggesting that it is not strictly of local derivation. It may equally be however that because the line of section does not truly parallel the direction of last ice movement in the area, it has narrowly missed recording the prescence of sandstone bedrock lying up-ice of this site.

FIGS. 34 & 35. Carboniferous bedrock area

Fig. 34 M.R. NT 420736

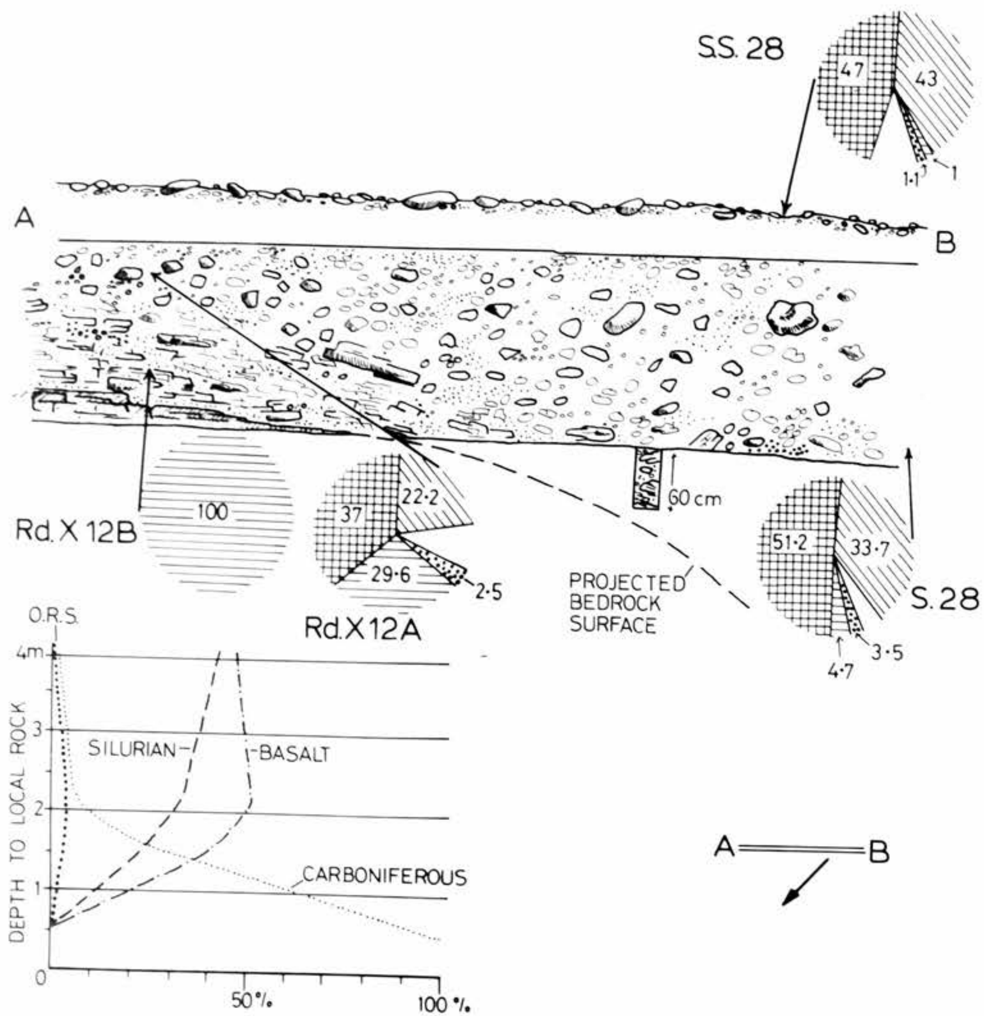
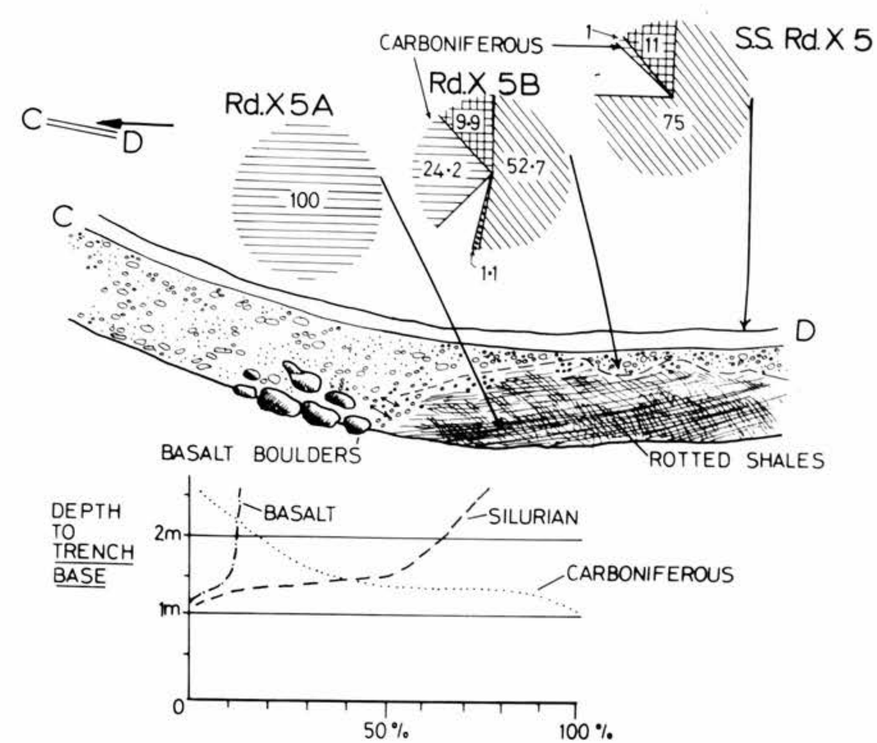


Fig. 35 M.R. NT 816425



CHAPTER FIVE

COUNTS OF A FINER SIZE FRACTION

In this chapter a number of stone-counts of a finer size-fraction than that examined previously will be considered. The samples examined were those taken from the base of the trench section. The method of collection was outlined previously in chapter three. The size of fragment considered in this chapter however was in the range of 100 mm to 160 mm. A hand lens or a simple binocular microscope (up to magnification x 40) was used in identification. One hundred particles were counted at most sites although in a few cases this was not possible. The minimum number counted at any one site was some 75 particles and the average content of the twenty samples examined was around 95 stones.

OLD RED SANDSTONE ERRATICS

Fig. 36 shows the results of this study with reference to counts of Old Red Sandstone erratics. Comparison is made with stone-counts (i.e. fragments 160 mm) from the samples studied and also with percentage weight of Old Red erratics in these stone-counts. The latter is included to give some idea of the size of stones making up the stone-count percentages.

In a comparison of stone-counts with fine-fraction counts in Fig. 36 a threefold division is suggested. Initially over most of the Old Red Sandstone bedrock area where the relative proportion of Old Red tends to be high in general, it is the stone-count percentages which are higher than the fine-fraction percentages by up to 20%. Immediately down-ice of this (samples 27 to 33 inclusive) however, there is a dominance of fine-fraction percentages although by lesser amounts. Percentages of both groups tend to be lower generally, representing this characteristic decline

FIGS. 36 - 40 incl. A COMPARISON BETWEEN STONE-COUNTS (BY % WEIGHT AND % NUMBERS) AND COUNTS OF A FINER SIZE FRACTION. (REF. CHAPTER 5 FOR DETAILS OF SIZES INVOLVED.)

FIG. 36 OLD RED SANDSTONE

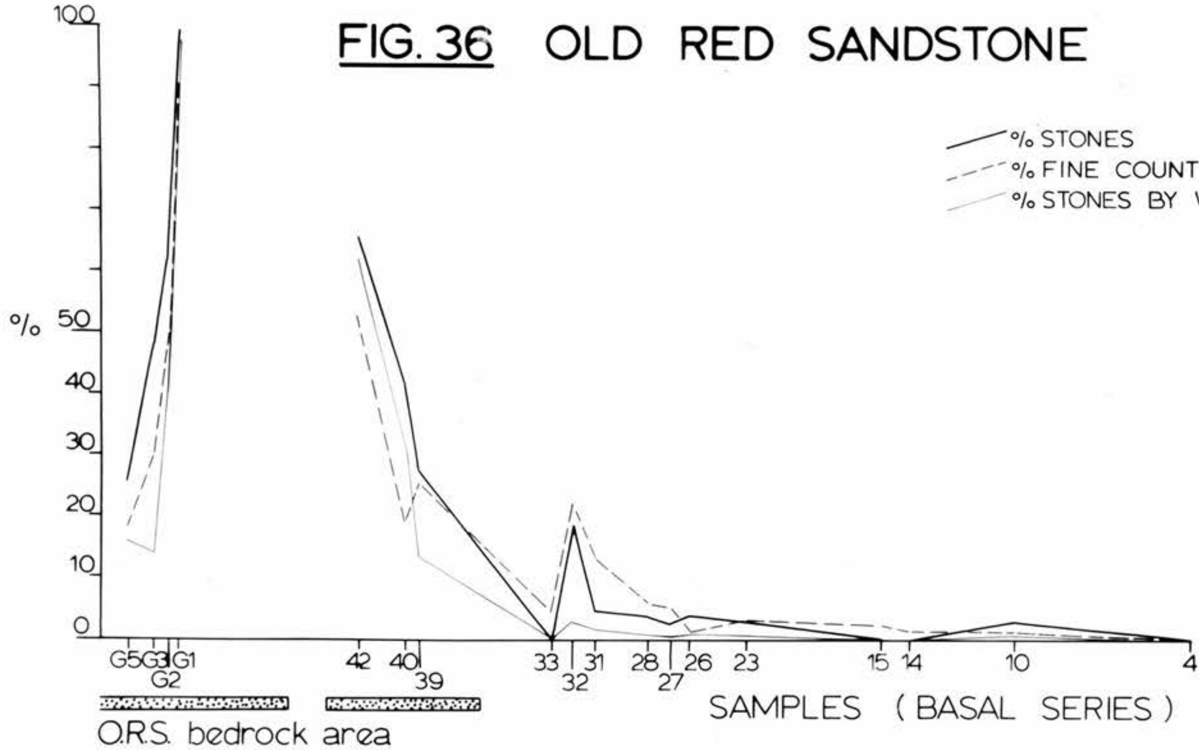
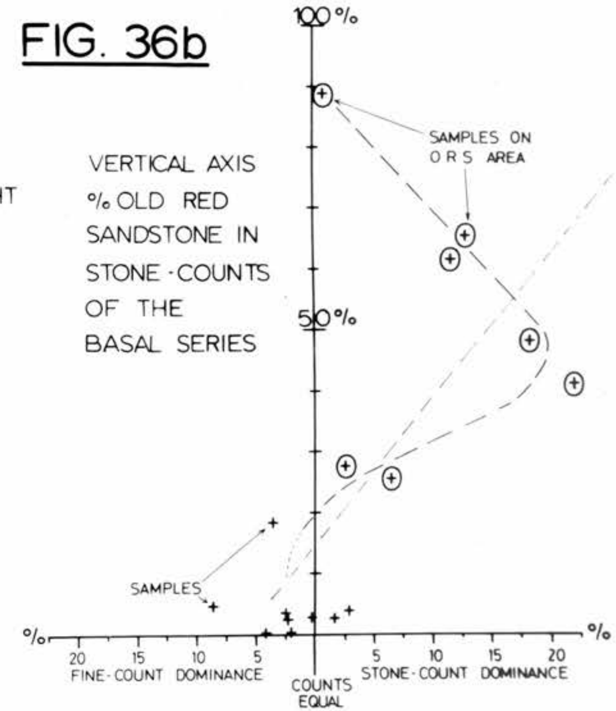


FIG. 36b



in the soft sedimentary erratics with distance from source. Down-ice of this again (samples 4 to 26) dominance of one group over the other is variable with only a slight tendency towards a more ubiquitous distribution in the finer fractions. The percentages involved in this case are very small (under 5%).

The results over the Old Red Sandstone bedrock area itself, while showing a general dominance of stone-counts over fine-counts, show a secondary pattern within this general one (Fig. 36b). When stone-counts of Old Red Sandstone are very high then counts of the finer fraction tend equally to be high. (E.g. sample S.G.1; stone-count of 89% and fine-count of 88%.) The fact that the percentage of Old Red Sandstone stones by weight reaches 97.6% is reflective of the position of this sample in till lying close to Old Red bedrock and dominated at all size levels by the local rock (; a till of the "intermediate till zone"). The high sand fraction in the particle size analysis of this sample (Fig. 13) is farther evidence of this. With movement away from bedrock and a fall in the Old Red Sandstone erratic counts an increasing dominance of larger Old Red fragments over the finer fraction is noted, reaching a maximum in S.40 in the samples examined. (Stone-count 41.2%, fine-count 19%.) With farther decline in Old Red stone proportions the dominance of the larger fragments declines again. Below about 20% stone-count concentrations the fine-counts begin to assume a slight dominance.

The significance of these trends will be discussed once evidence has been examined from the other erratic groups.

BASALT ERRATICS

A broadly similar pattern of change and relative dominance is evident in the counts of basalt erratics. This is especially true if the pattern about the main basalt bedrock area and down-ice of it are examined. In samples on the basalt bedrock area (Fig 37 samples S.33 and 32). it is the stone-counts which are dominant over the fine-particle counts by some 10 to 15% in the samples examined. This is particularly

FIG. 37 BASALT.

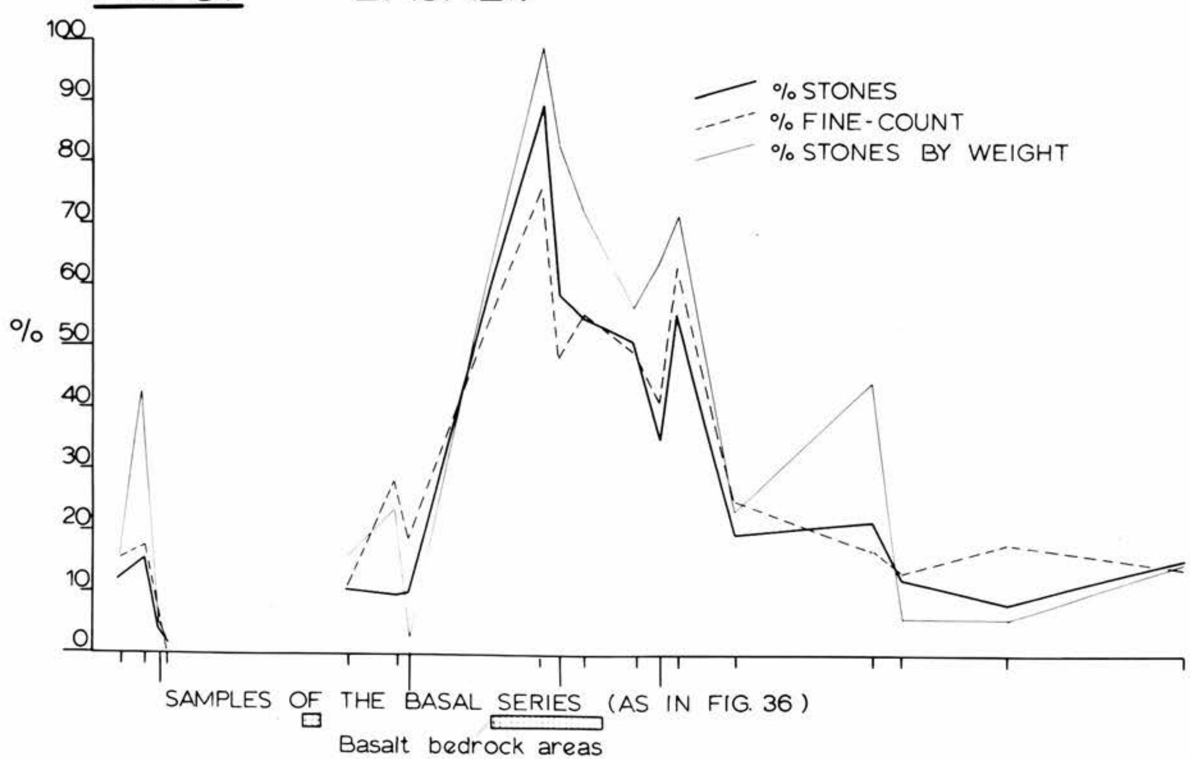
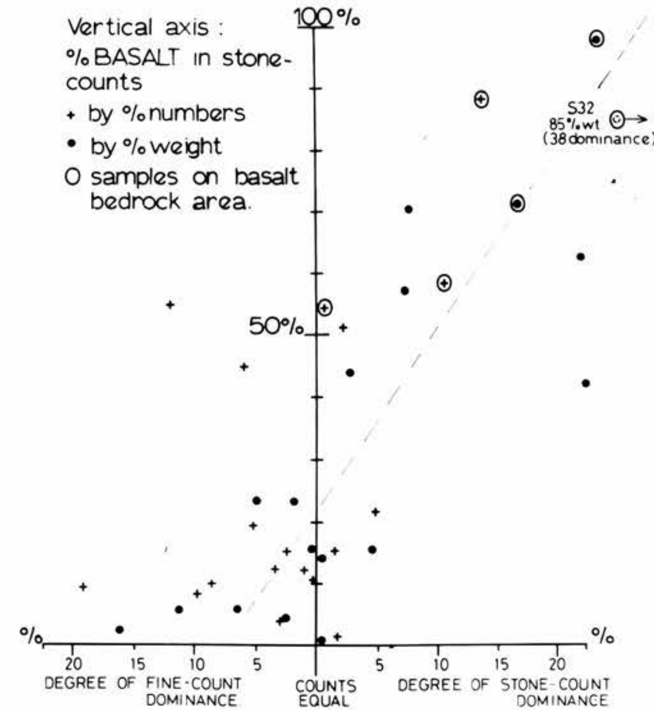


FIG. 37 b



emphasized when comparing the percentage weight of stones with percentages of this finer fraction (with differences up to 36%). This comparison is not an invalid one in that comparison is being made between weight of stones on the one hand and numbers of fine fragments on the other. In this instance, percentage counts of the fine fraction may be regarded as being the same as percentage weight in that group since the size range of the group is such a limited one.

Down-ice of the main basalt bedrock area the stone count percentages cease to dominate those of the finer fraction and the pattern is generally less clear. In terms of percentage weight, the basalt stone-counts do remain dominant as far onto the Carboniferous area as sample S.15. The percentage numbers in the stone-counts however tend generally to be lower than those of the fine-fraction counts initially (S.28 to S.23). Such variations as do exist in this area might be considered to be well within the errors of the sampling technique and where no consistency of dominance is achieved by either group it is perhaps invalid to make too much of these fluctuations. Fig. 37b suggests broadly a dominance of larger fragments where high stone-count percentages are involved and a tendency towards a slight dominance of fine-fraction counts where lower stone-count percentages are involved, i.e. generally farther away from the source area.

Up-ice of the main basalt area basalt concentrations in the fine-fraction are slightly greater than those in the stone-counts. The percentage weight of basalt stones varies considerably however but since percentage numbers are small, thus allowing one large fragment to considerably alter the percentage weight figure, this is perhaps less significant in this instance. This is also true to some degree of basalt erratics found towards the east of the Carboniferous study area.

THE CARBONIFEROUS ERRATICS

The Carboniferous bedrock is essentially similar in rock types to that of the Old Red Sandstone area but the patterns noted in Carboniferous erratic counts are less clear than those of the Old Red Sandstone erratics. The major complicating factor in this instance appears to be the depth of till overlying bedrock, i.e. more specifically the distance of most Carboniferous erratics from their source. Only in one site examined does the Carboniferous stone-count reach as high as 30% (S.27, Fig.38) and this is at a point in the section quite close to bedrock (Fig. 34). Here the fine-fraction count follows the pattern noted previously close to local bedrock in both the basalt and Old Red Sandstone bedrock areas and is some 14% less than the stone-count at this site. (The site lies well to the west in the Carboniferous bedrock area and would not therefore be expected to contain great quantities of Carboniferous erratics from up-ice.)

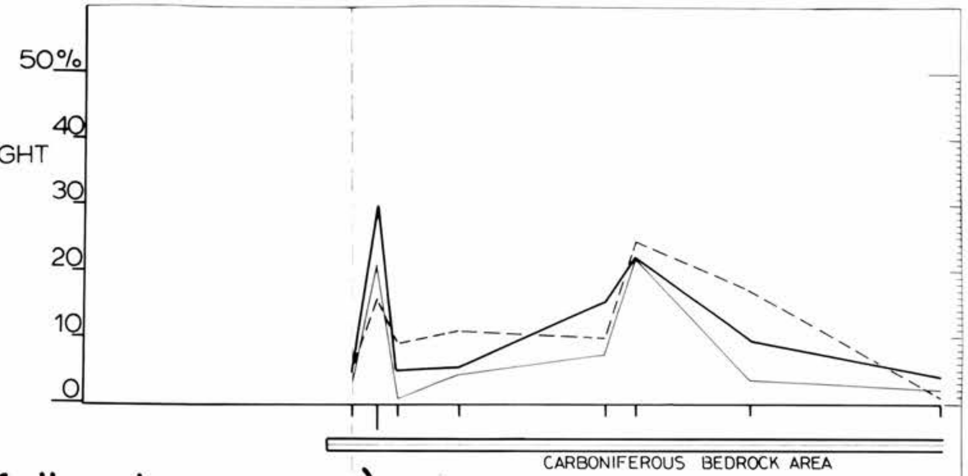
Elsewhere in the Carboniferous area, bedrock was not evident at all inthe section in the region of any of the samples examined in Fig. 38. Higher stone-counts of Carboniferous erratics did exist in sample S.14 and to a lesser degree in S. 15, farther east in the Carboniferous area than S. 27. The fine-fraction count did not fall to the same degree as in S.27 however, being only 5% less than the stone-count in S.15 and actually 2% more in S.14.

Distance from bedrock source is thus again shown to be a major factor in determining the relationship of stone-count percentages to percentages of this finer size-fraction for any erratic group. Such a pattern is evident to varying degrees on three different geological groupings, two sedimentary groups and one volcanic group, thus showing its applicability to differing geological type. It seems that it is the coarser fragments which are most in evidence when a new rock becomes incorporated into a till. Dreimanis and Vagners (1971) have pointed to

FIG. 38 CARBONIFEROUS

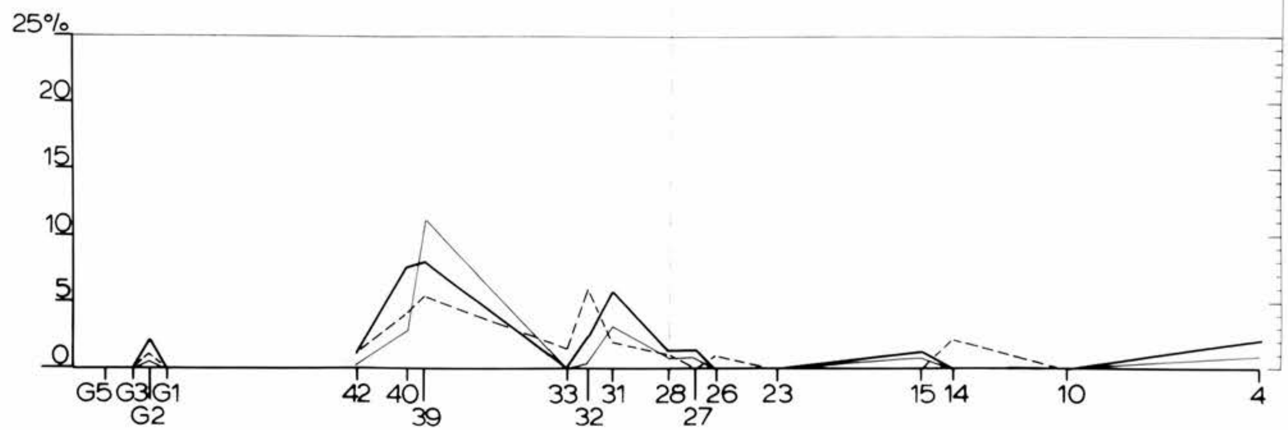
% STONES
% FINE-COUNTS
% STONES BY WEIGHT

The above symbolism also applies to fig. 40.



(FIG. 39 : See following page)

FIG. 40 TRACHYTES



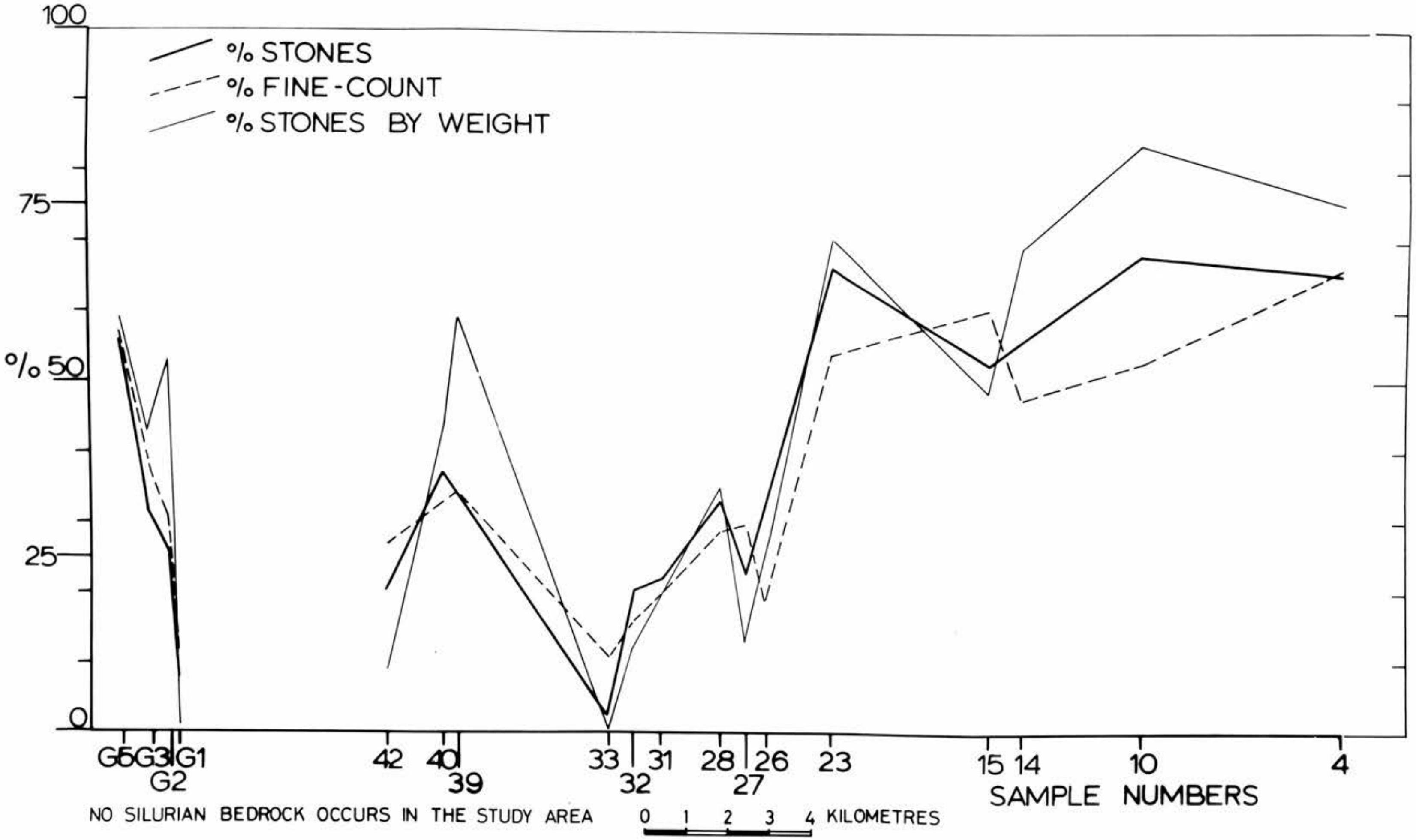
SAMPLE NUMBERS - ALSO APPLY TO FIG. 38 (FROM S.28 DOWNWARDS).

this abundance of local material in the coarse fractions as giving an impression that the local material predominates in the till at all size levels. There is some exception to the general rule in that in some instances where the "intermediate till zone" is well developed one does have a till of almost 100% local material. Where the local material is being incorporated into a more truly mixed basal till however, results suggest that the greatest initial increase is in the coarser fraction. Beyond this area of dominance of the coarser fraction, a slight domination of the particular finer-size fraction examined here was suggested over the stone-counts. Dreimanis and Vagners (1971) have suggested that the frequency polygon of any rock material in till is bi-modal, (the peaks being in the larger coarse fraction and the terminal grades of the constituent minerals). Between these two points the distribution curves for particular rocks approach straight lines when crushing is the main mechanism of comminution. It is suggested that any deviations from straight lines would therefore indicate that processes other than crushing have also participated in comminution. Thus the results examined above in areas down-ice of those sites dominated by local coarse material merely represent one end of this cumulative curve and given any degree of crushing contributing to comminution, greater counts of any one rock type might be expected as the size range being counted was decreased.

SILURIAN ERRATICS

Fig. 39 shows a comparison between stone-counts and "fine"-counts of the Silurian erratics. In this case there is no area of Silurian bedrock occurrence within the study area. This examination therefore deals with only part of the sequence discussed previously. In the light of the evidence noted above, and with the great distances of the Silurian material from its source a gradual increase in domination of the finer size-fraction counts over the stone-counts might be expected, especially

FIG. 39 SILURIAN.



NO SILURIAN BEDROCK OCCURS IN THE STUDY AREA towards the east of the study area.

This does not appear to be the case, Over most of the Old Red Sandstone bedrock area there is a very slight dominance of the fine-fraction counts of Silurian erratics over stone-counts but this is so small (maximum of 6.8%) that it is well within any potential sampling error. Its consistency tends to lend it some validity however. Down-ice of this over the basalt and Lower Carboniferous bedrock areas no absolute dominance is established. The stone-count percentages are cumulatively only marginally greater than those of the finer fraction. In samples on the Carboniferous area for example (S.4 to S.28 inclusive) the cumulative percentage of Silurian stone counts is 399.5 while that of the finer size fraction is 358.7. The high percentage of often sizable Silurian erratics well into the Carboniferous area has already been noted in the consideration of the basal and surface series of stone-counts in chapters three and four respectively. Some reasons for this have already been suggested. Some of these can now be recalled in the light of this new evidence.

It has previously been suggested (chapter 3) that much of the Silurian material might be seen as being derived from higher levels in the basal ice and deposited as a till only during the final stages of weakening ice movement and ultimate decay. This material would originally be incorporated deep into the ice by active shearing movements in the basal ice over the very variable Silurian terrain and also in part over the irregular Old Red Sandstone topography with its frequent igneous masses. For much of its existence in the englacial environment therefore, this material was generally clear of the most active basal ice where erratics would be most subject to crushing (Dreimanis and Vagners 1971). At these higher levels, with movement being generally less active and less violent, the erratics would be relatively less subject to crushing and it seems possible that abrasion might be a more significant agent in this environment, (as witness the extreme rounding of Silurian fragments over the Carboniferous bedrock area). The upper two metres or so of till in the Carboniferous area, as exposed in the section, therefore tend to contain much of this distant material. It appears to have been transported fairly high in the ice, possibly in horizontal dirt or debris bands, and somewhat removed from the really active basal ice during the most powerful phases of ice movement. The often small size of Silurian erratics of the basal series found over the Old Red Sandstone bedrock area (ref. chapter 3) and the very slight, but consistent, dominance of the finer size-fraction over this same area also tend to support such a hypothesis. The thinner tills over much of the Old Red Sandstone area mean that tills at the base of the trench are potentially more often down to the true basal tills deposited from the base of active ice. The Silurian fragments in these tills might therefore be more liable to crushing in the active basal ice.

Fig. 40 shows a comparison between stone-counts and counts of the finer size fraction in erratics of the trachyte-felsite group. No particular trend or dominance of one group over the other is evident, and both total amounts and differences involved are relatively small, especially farther east, in the Carboniferous bedrock area.

In this consideration of the relationship between stone-counts and 'fine'-counts in the last section, one major qualifying factor must yet be mentioned. Results in each case are essentially expressed in the proportional relationships of one erratic group to the other and thus apparent trends in one or more groups from one sample to another may in reality be caused by a rise or fall in concentrations of another group. For example, it has already been shown that sizes of basalt fragments decline considerably eastwards in the Carboniferous study area (Fig.21) and yet this is not apparently reflected in any great rise in 'fine'-counts of basalt in relationship to stone-counts as might have been expected. One possible explanation not yet referred to is that the fine-counts of most other erratic groups are also increasing along with the basalt. Thus in any sample count of this finer fraction the erratics maintain almost the same relationship one to the other as before. To detect such an occurrence it would be desirable to construct complete cumulative curves of the various size ranges for individual erratic types by working from a constant size of till sample at each site. In this way the behaviour of the different erratics and their destruction with distance from source could be more closely and objectively studied. This was not possible within the scope of the present thesis. Bearing this qualification in mind however it is still maintained that a pattern is evident from the existing studies as described above.

CHAPTER SIX

"WIDE-AREA" SURFACE STONE COUNTS (F. and F.A. Series)

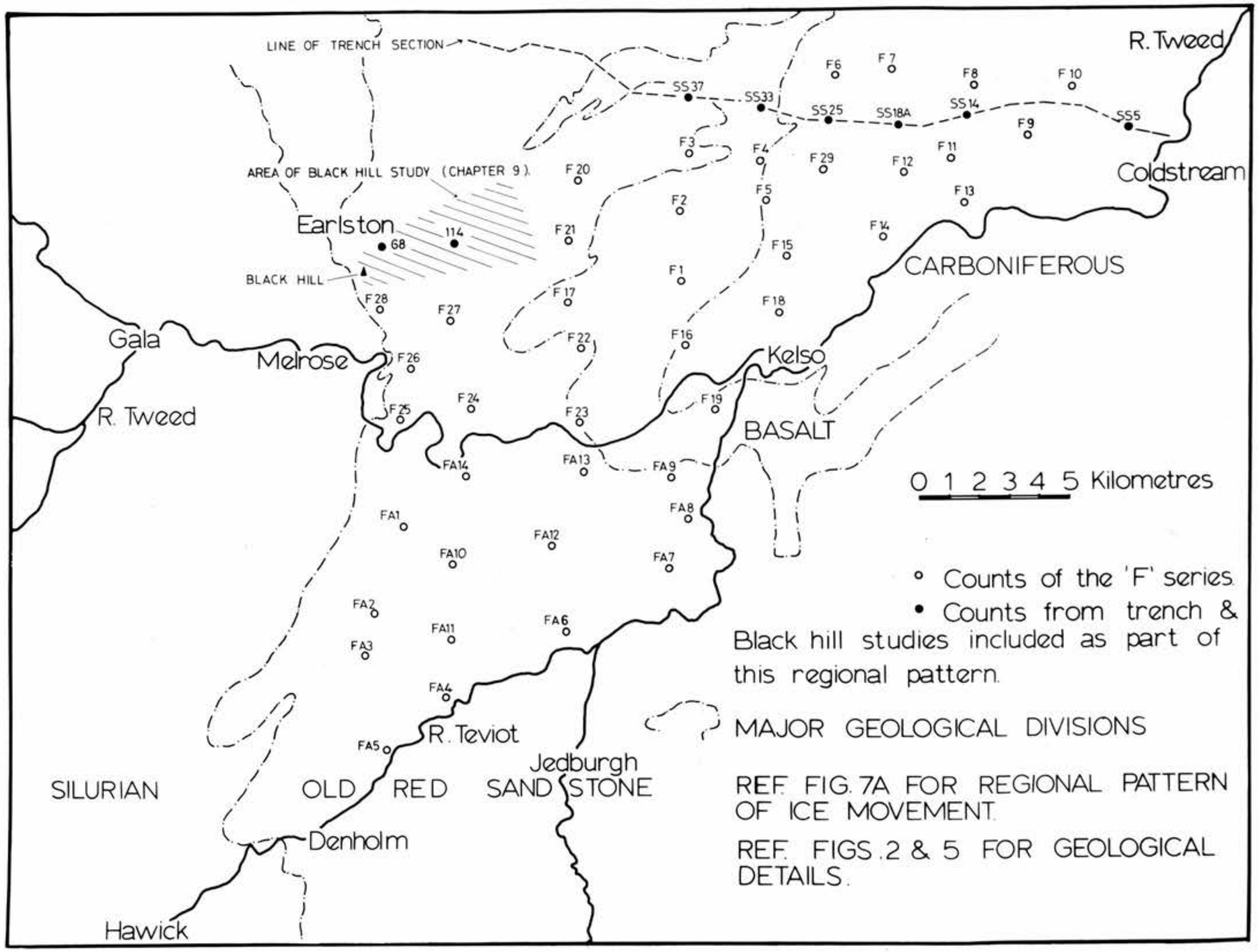
INTRODUCTION

Thus far, although detailed stone-count studies have been examined, these have been limited to the region of the pipeline section. There was therefore a need to relate this detailed evidence to a much wider area of the Tweed basin. Certain relationships between tills of the "basal series" and surface tills have already been suggested (chapter 4). Thus a series of surface counts studied from a wider area could be related to geological change, depth of till where known, and to the evidence from the trench section. Results from such a study could therefore be interpreted in the light of the trench-line results.

THE AREA

A series of samples was taken in the pattern illustrated in Fig. 41 with intervals of two to four kilometres between samples. The southern boundary of the area was the river Teviot between Hawick and Kelso and thereafter the river Tweed from Kelso to Coldstream. The trench section formed the northern boundary except in the Carboniferous area where studies extended 1-2 km northwards. To augment the stone-counts use was made of samples from the S.S. series of surface counts (chapter 4) where these fitted into the grid, and similarly of samples 68 and 114 from the Black Hill studies (chapter 9). The area chosen was thus of greatest extent in the direction parallel to ice movement, giving an integrated series of results for interpretation. The geology of the area is shown in Figs. 2 and 5.

FIG. 41. LOCATION MAP OF SAMPLE SITES FROM THE WIDE-AREA ('F' SERIES) STONE-COUNTS.



SAMPLING

The general area for sampling was chosen on the map, based on a loose grid pattern. Where possible, ploughed land was sought for sampling in the general area chosen. The deeper furrow adjoining ploughed sections was taken and a further 30 cm of soil removed. In some cases (e.g. permanent grass) more digging was necessary and some 40-60 cm depth of soil were removed. Sample sizes ranged from 100 to 137 with the mean being 108. 43 samples were taken in this way and with these are considered the two from the Black Hill study and six from the S.S. series associated with the trench. All are shown on Fig. 41. Stone size was as adopted for the basal series of counts from the trench study (Chapter 3) as this had proved quite workable (generally stones greater than 160 mm).

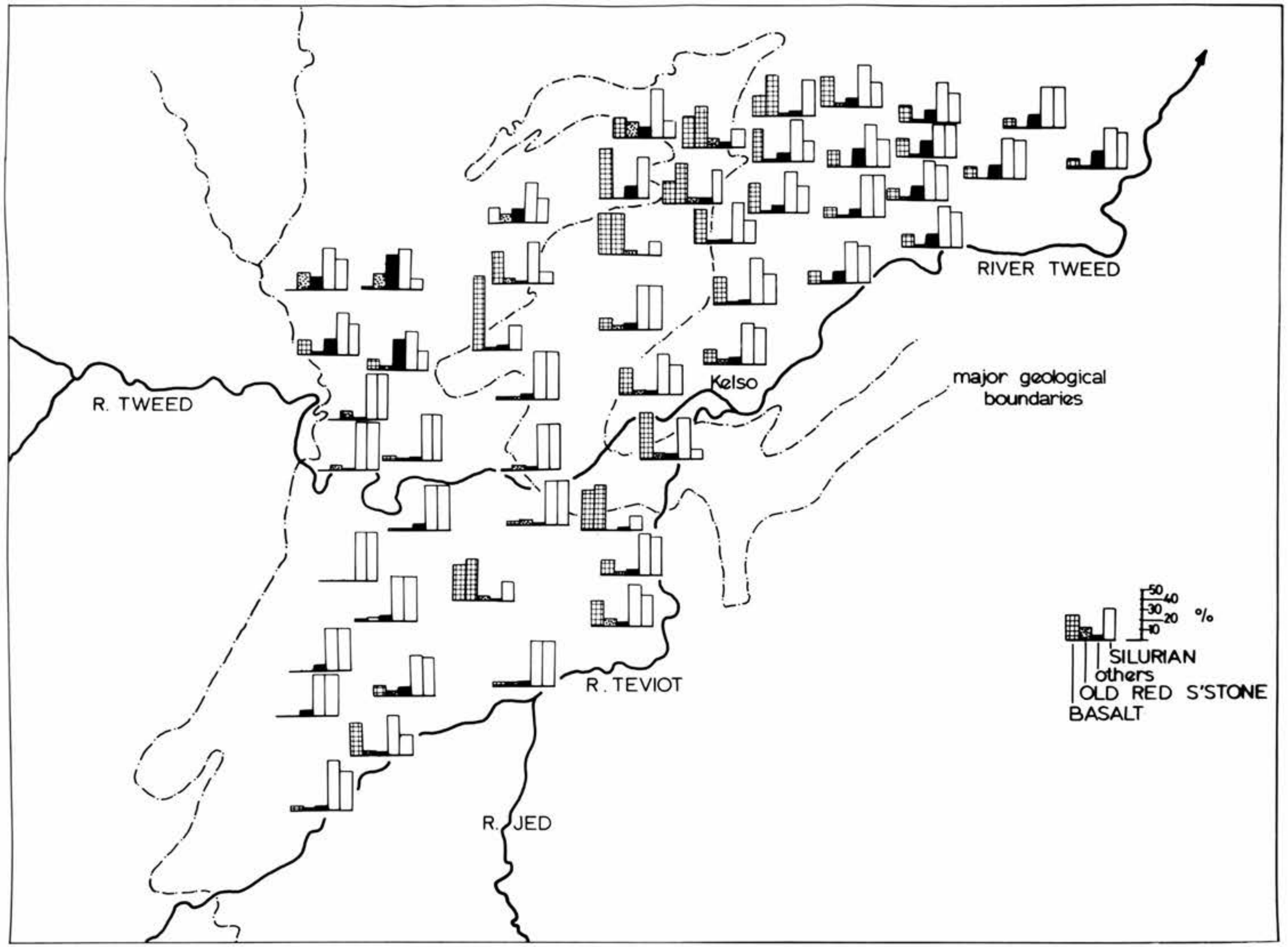
THE RESULTS

The general pattern of results in the major erratic groups is indicated in Fig. 42. Patterns are more readily apparent if the more important constituent groups are examined independently.

Silurian and Basalt erratics Fig. 43 shows Silurian concentrations and Fig. 44 shows basalt concentrations. Contours have been interpolated at 10% intervals. While not having the statistical accuracy of a computerised trend surface, their limitations are quite acceptable in this instance.

Patterns are immediately recognisable, particularly the co-incidence of Silurian peaks with basalt troughs and vice-versa. It has already been suggested from studies of the S.S. series of surface counts (Chapter 4) that neither the Old Red Sandstone nor the Carboniferous erratics regularly reach high percentages in surface counts and reasons for this were suggested. This again appears to be the case in these "wide-area" stone-counts and it is the interdependence of Silurian and

FIG. 42 'WIDE-AREA' STONE COUNTS : GENERALISED PATTERN OF RESULTS



basalt percentages which is in many ways the most critical evidence. Over much of the Old Red Sandstone bedrock area Silurian percentages are high (Fig. 43), especially where tills are known to be deepest. Silurian counts drop markedly in certain areas examined however. In each case local bedrock influence appears to be the critical factor and most of this derives from the many igneous intrusive bodies in the area. Samples FA9 and FA12 provide possibly the clearest examples of this. FA9 lies in the lee of the massive Peinel Heugh basaltic intrusion (Fig.5, ~~M.R.~~ NT 654264), and shows only 13% Silurian as against 85% basalt. FA12 lies on the even larger Fairnington intrusion (Fig.5) and shows only 19% Silurian compared with 75% basalt. A more limited influence is seen in sample FA4 in the lee of the smaller Minto intrusion near Hawick, which has 33% basalt and 61% Silurian. It is at this point however that the whole system of sampling and the contour patterns portraying this begin to show apparent shortcomings. Fig.5 shows the wide distribution of igneous intrusive bodies in the Old Red Sandstone area. To produce a pattern of surface stone-counts that could adequately cover the very local changes in till composition caused by these bodies would involve a very much more detailed system of sampling than that undertaken here. A very detailed study was later made around the trachyte intrusion of Black Hill near Earlston. This is examined in Chapter nine. With a grid pattern of the dimensions used in this instance, there could be a danger of gaining a false impression of erratic concentrations either by constantly sampling on or close to these intrusions or alternatively, consistently sampling in between the intrusions. In this instance however adjustment was made from a completely regular grid so that samples were taken to represent both these situations; i.e. samples were taken from sites between known intrusions and also from sites on some of the major intrusions themselves. While it may be that in many instances high basalt concentrations around some intrusions may have been missed by the sample spacing, or equally higher Silurian counts in some of the

FIG. 43. SILURIAN CONCENTRATIONS (%) IN STONE - COUNTS OF THE MIDDLE TWEED AND TEVIOT BASINS.

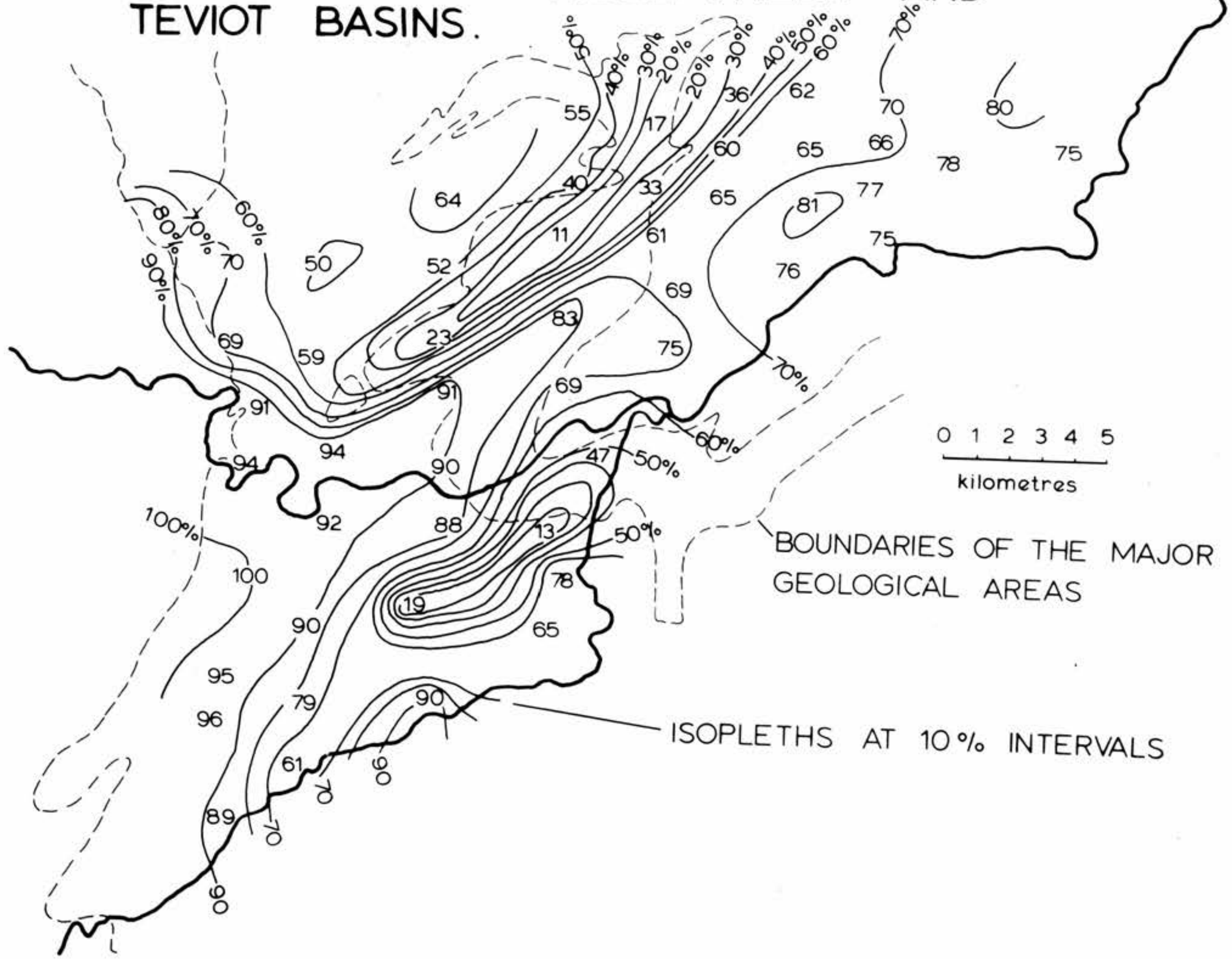
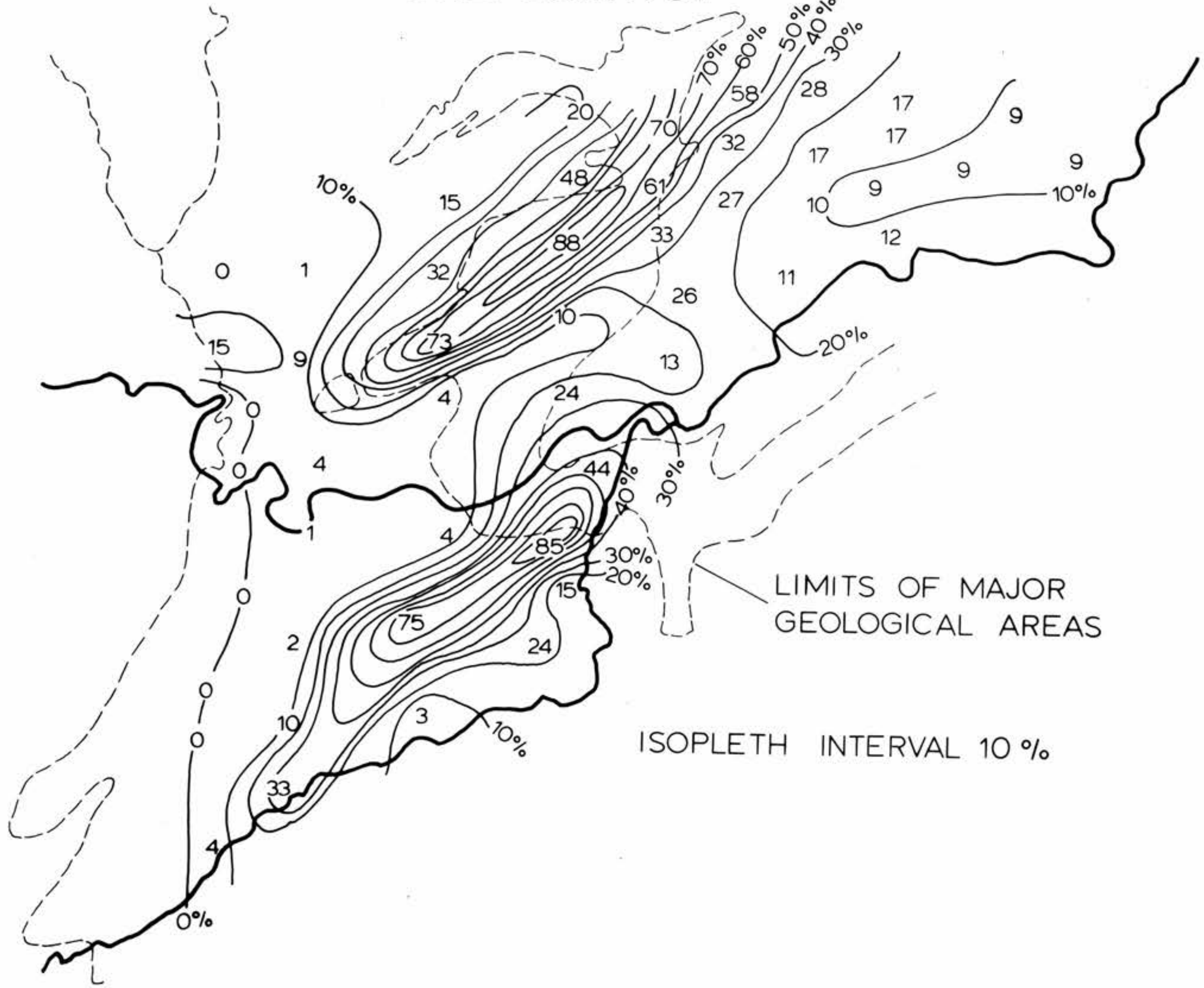


FIG. 44. BASALT COUNTS (%) IN "WIDE-AREA" (F) SERIES STONE-COUNTS.



intervening lowlands, it is still possible to accept the generalisations offered by this relatively widespread grid pattern. This provides an overall picture of patterns and trends, particularly if studied in the light of what is already known of geology, relief, depth of till and the knowledge of relationships between surface and "basal" tills gained in trench-based studies.

High Silurian percentages tend to occur towards the centre of the basin where tills are known to be deeper on the lower ground. This belt of high Silurian counts is narrowed at the point where the Kelso Lavas swing across the Tweed valley. Down-ice of this onto the Carboniferous area, Silurian counts are over 60% of all erratics in most parts, increasing down-valley to a maximum of 80% in sample F.10 (Fig.41). Silurian concentrations are lower towards the northern and southern limits of the study area where igneous rocks are most in evidence and tills are generally thinner on the higher ground. The high ridges of the Kelso Traps in the Smailholm and Hume areas stand out particularly clearly as areas of greater basaltic influence with correspondingly lesser Silurian concentrations (samples F.1, F.2, F.4 and F.17). This follows the pattern established in the trench section where tills on this higher ground were very much thinner and local bedrock influence reached through to the surface at a very short distance down-ice from bedrock occurrence.

Basalt percentages are very low in the west of the study area with only a few intrusive basalt bodies contributing to tills derived from the Silurian bedrock area. Eastwards, as basalt intrusions increase in size and frequency, basalt percentages in stone-counts rise. They are dominant on the lavas encircling Kelso, especially in the Smailholm and Hume areas. Sample F.2 near Smailholm recorded 88% basalt on ploughed land. Along this part of the Kelso lavas, surface bedrock exposures are frequent. Particularly important are the crags of olivine-basalt at Smailholm Tower (N.T. 638347) and the ice-moulded forms around Hume village (N.T. 705415). In these areas tills are often thin, constituting only a thin cover of angular basalt fragments over bedrock.

Sample F.19 on the other hand, although on the down-ice side of the basalts, registered only 44% basalt. Sample F.16, also on the down-ice edge of the basalts, showed only 24% basalt as against 69% Silurian. These samples lie towards the centre of the basin and the relatively lower basalt percentages reflect this tongue of higher Silurian concentrations pushing over the Kelso Lavas in this area. Ragg <u>et al.</u> (1960) have already suggested this greater Silurian influence in these central areas based in that instance on the mineral content of soils as well as on some stone-counts. Depth of till has been suggested as one of the critical factors in determining the amount of local rock in surface tills. (The nature of the bedrock topography might also be important, particularly in its impact on shear-plane activity in the basal ice.) Results here would therefore suggest deeper tills towards the centre of the basin, yet also perhaps point to a more powerful streaming of ice through the central area carrying Silurian influence over the local rocks, including the Kelso Traps, and deep into the Carboniferous area.

Basalt percentages decline eastwards over the Carboniferous area. Less than 2 km down-ice of basalt bedrock they have fallen to under 30% but thereafter the decline is more steady until a level of about 10% appears to be held in the east of the study area. This halt in the decline of basalt concentrations in the east may in part be due to influences from the arm of the Kelso Lavas lying south of the Tweed below Kelso (Fig. 2).

Over the Carboniferous area basalt counts tend to be higher in the north in the lee of the lee of the higher parts of the lava body and away from the tongue of Silurian influence down the centre of the basin.

This consistent presence of at least 10%, and often 20% or more, basalt in surface counts is perhaps in itself surprising in view of the comparative lack of Old Red Sandstone or Carboniferous erratics in these situations. Reasons for this have already been offered however (Chapter 4) and can be condensed to two main points:-

(a) the relative susceptibility of sedimentary erratics to englacial erosion (attrition) and,

(b) the very active erosion of the prominent basalts and the active englacial movement of basalt material upwards into the ice along shear-planes developed over these high craggy areas.

East of the basalt lavas and into the main part of the drumlin field intrusive bodies are very limited and the pattern is thus less complex than that encountered in the Old Red Sandstone area.

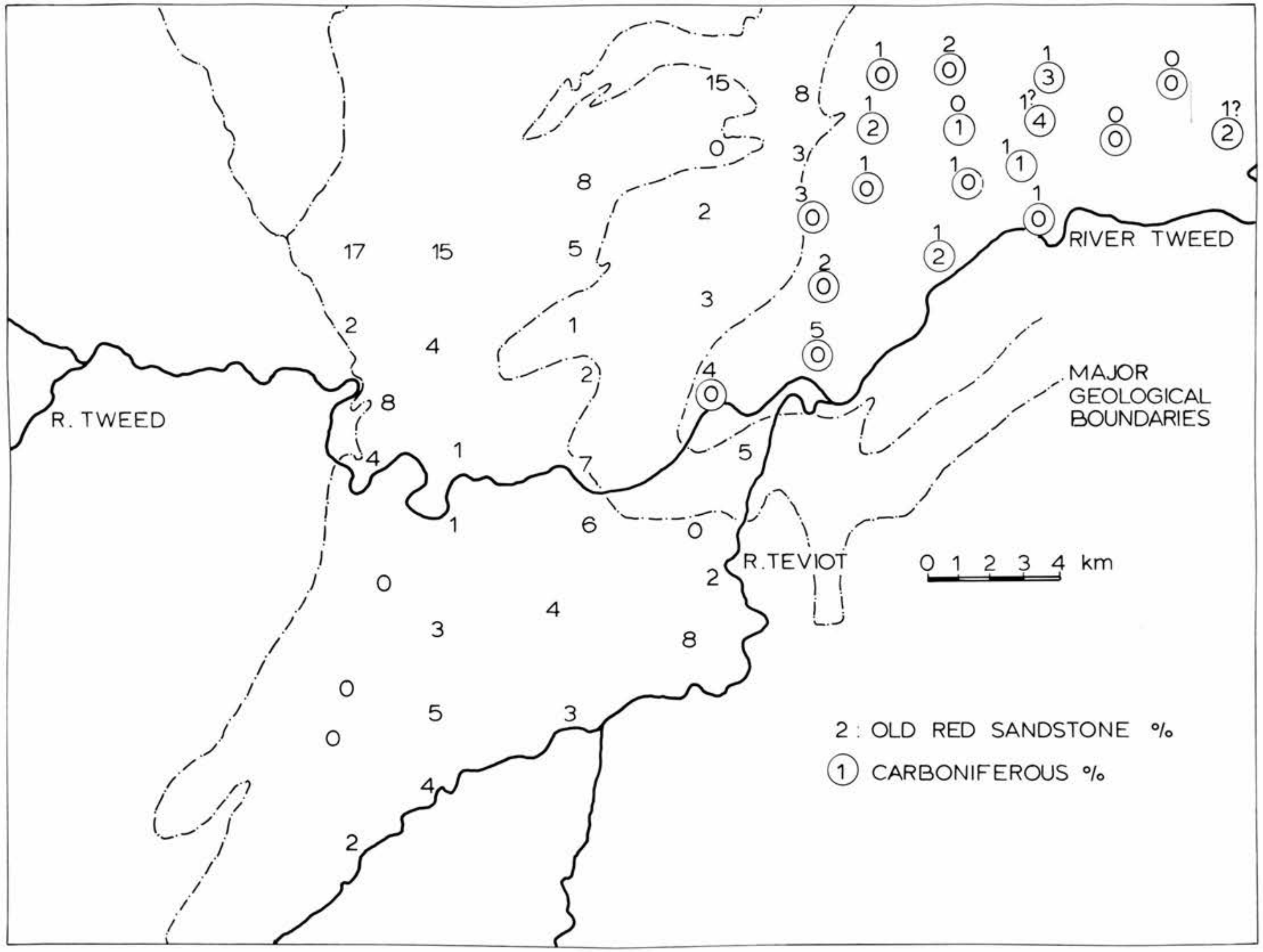
The Sedimentary Erratics - Old Red Sandstone and Carboniferous

Fig. 45 shows the Old Red Sandstone and the Carboniferous erratics counted in the "wide-area" series of counts. It is immediately apparent that neither achieves great proportions at any of the sites examined. The maximum surface count in Old Red Sandstone is 17% with two other counts at 15%. The maximum surface concentration of Carboniferous in this series reached only 4%. (Such a figure is perhaps an abnormally low concentration, caused by the particular sampling grid adopted. Counts of up to 20% Carboniferous concentration were in fact recorded in surface counts elsewhere in the study area. These are discussed at the end of this chapter.)

The areas of higher Old Red Sandstone counts fall generally into two categories:

1. Towards the east of the Old Red bedrock area. Tills on the Old Red Sandstone area are in general less deep than those of the Carboniferous area and particularly so away from the centre of the Tweed basin. It is

FIG. 45 CARBONIFEROUS & OLD RED SANDSTONE CONCENTRATIONS IN 'WIDE-AREA' STONE COUNTS.



reasonable therefore to expect significantly increased surface concentrations of Old Red Sandstone erratics towards the east of the Old Red Sandstone bedrock area. The fact that for the most part these do not occur is only partly due to the depth of till overlying bedrock It is also due in part to the inability of the Old Red Sandstone erratics to survive transportation and to the exotic origins of this material let down from high in the basal ice druing melt-out. Sample S.S.37 (Fig.41) reaches 15% concentration of Old Red Sandstone in the depression south-east of the East Gordon ridge. This site has already been discussed in detail in Chapter 4 (Fig. 33, site 3).

2. At higher, more exposed sites of Old Red bedrock. In general it is the Old Red Sandstone which forms the low ground between the more resistant intrusions but in a few cases Old Red sediments occur on the higher ground. As such they are usually in areas of more vigorous glacial erosion and of thinner tills where local bedrock influence at the surface is correspondingly greater. Two such sites are illustrated by the two samples included from the Black Hill study. These sites (68 and 114, Fig. 57) show Old Red Sandstone counts of 17% and 15%. These are not high in absolute terms but are certainly so in terms of a surface count of Old Red.

Sites 1, 2 and 3 as discussed in the latter part of Chapter 4 (Figs. 31-33), illustrate the significance of these high Old Red Sandstone counts. Surface counts of 13%, 3% and 15% respectively were encountered at these sites yet at no site was Old Red bedrock more than2.50 m below the surface. Indeed concentrationsof 100% Old Red Sandstone rock were considerably closer to the surface than this in the "intermediate till zone" lying above bedrock.

The two sites from the Black Hill study occur in slightly differing situations. Site 68 sits on the northern flank of Black Hill itself and is a flattish site on a pronounced shoulder. The till in this area, is thin, and dominated by a Silurian count of 70%. (The other 13% is trachyte.) Old Red Sandstone influence comes from a band of sandstone lying between the intrusive rocks and the Silurian strata to the west, then skirting around the flank of the hill, much of it perhaps having been eroded from this shoulder. The second site lies high on the stoss end of an ice-moulded ridge to the south-east of Black Hill. A pronounced erosional depression lies parallel to the long tail of Black Hill on its southern side. South again of this depression the land rises onto the broad flat ridge where Old Red Sandstone percentages are occasionally higher. The till is obviously deeper than at site 68 (and indeed is ploughed land), yet in the light of previous evidence the 15% Old Red Sandstone concentration would suggest till whose maximum depth might be 2 m. The sandstone is of fairly local derivation because of the relatively limited up-ice extent of the Old Red Sandstone bedrock area and thus a till of considerably less than 2 m is likely. In the light of the wide spread of trachyte erratics noted in the Black Hill study (chapter 9) it is possible that some of the Old Red Sandstone erratics may even derive from higher on Black Hill itself. (A count of 28% trachyte was recorded at the site.)

Down-ice of the Old Red Sandstone bedrock area Old Red erratics do not appear to survive on or beyond the basalt lavas in any numbers. This echos results from the pipeline section (chapters 3, 4 and 5) and reasons need not be repeated.

Tills overlying the Carboniferous bedrock area are very deep in parts (chapter 1) and surface tills are Silurian dominated. Carboniferous counts at sites examined ranged from 0 to 4%. It is difficult to argue about any overall pattern based upon such a small number of counts with a small range. Results from the S.S. and 'basal' series in chapter 4 on the other hand do suggest that any Carboniferous count at all may

may be significant in a surface sample.

Sites 4 and 5 as examined in chapter 4 (Figs. 34 and 35) both showed Carboniferous bedrock within the section. In site 4 where bedrock was seen at about 2 m depth, the surface count of Carboniferous reached only 1%. In site 5 bedrock came to within 1 m - 1.50 m of the surface yet a surface count of only 11% was recorded. Results like these suggest that a surface figure of only 4% as in S.S.14 may therefore reflect the near-presence of Carboniferous bedrock. At site 5 it is significant that the 11% Carboniferous content of the surface till was not of the same rock type that immediately underlay it. This recalls one of the major difficulties in interpreting these results, i.e. that the content of a surface till is not representative of bedrock immediately beneath it but rather of bedrock some unspecified distance up-ice. This distance will vary in direct proportion to the depth of till at any point, depth of till in turn being the result of the interplay of glacier mechanics, debris load and bedrock topography.

In some instances, e.g. very high counts of Old Red Sandstone or Carboniferous erratics, the depth of till is suggested with some degree of certainty but with counts below about 10% and certainly below 5% it becomes much more difficult to confirm or deny the existence at any site of bedrock close beneath the till surface. With the suggestion of considerable depths of till over much of the Carboniferous area (chapter 1), and the relative lack of bedrock, in the Carboniferous sections of the pipeline trench (chapter 2), it seems most likely that the majority of these results merely indicate at a particular site the known inability of the Carboniferous erratics to reach these higher till levels in any quantities, thus implying till depths of at least 2-3 m. Reasons for the non-survival of the Carboniferous erratics at these levels lie in the ease of attrition of these erratics during transport and in the mode of deposition of these higher levels of deeper tills, particularly relating to the more exotic origin of the material that was melting out at the end of the depositional phase. (The derivations of this material and the processes involved in its occurrence have been discussed in chapter 2 and will be related to the general stone count evidence more fully in chapter 10.)

The Todrig Drumlin Study. (N.R. NT 789420)

A detailed study of local surface stone-counts was carried out on one particular drumlin feature at Todrig farm, east of Eccles village. The object was to examine possible local variations in surface stone-counts, particularly in relation to drumlin morphology. This particular drumlin was chosen for several reasons.

(a) Permission had been gained to sample freely in this area.

(b) Conditions for ease of sampling were met.

(c) The pipeline section crossed this drumlin, thus providing additional evidence - samples S.S.13 and S.S.14 were used in this study.

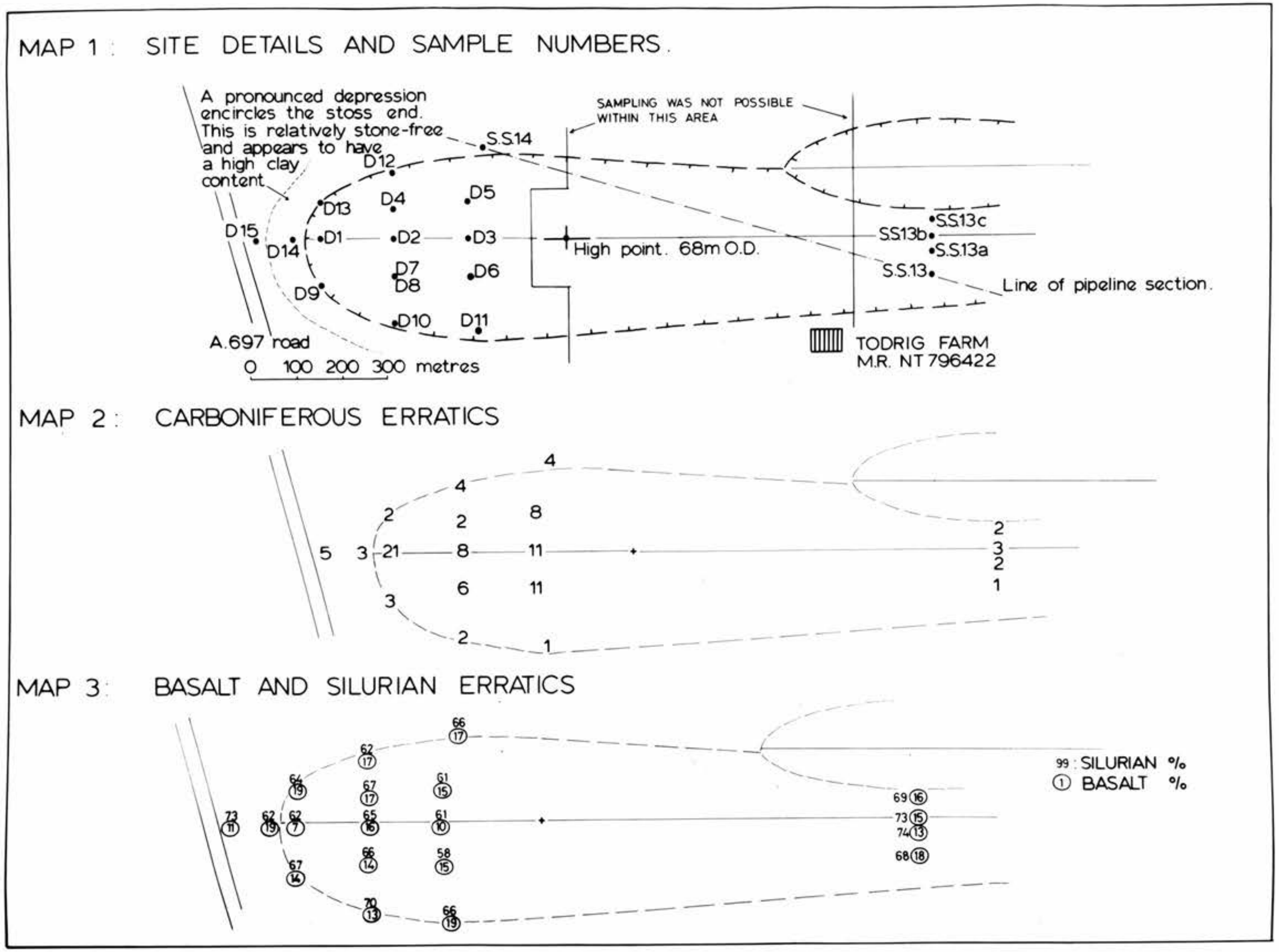
(d) The stoss end of the drumlin was particularly interesting (Fig. 45a). A pronounced depression preceded the drumlin and preliminary examination of the stoss end at the time of pipeline studies had revealed Carboniferous erratics in notable quantities near the surface. This was considered worthy of further investigation in view of the apparent general lack of surface Carboniferous erratics elsewhere.

All counts were made on ploughed land in the manner described previously.

Results of the Todrig drumlin study

Results are shown in Fig. 45a. Counts of Carboniferous erratics are most interesting. Out of 19 counts, 7 are above the 4% maximum

FIG. 45a. SURFACE STONE-COUNTS ON THE TODRIG DRUMLIN.



encountered elsewhere in the "wide-area" surface counts. Dominating the counts is a 21% concentration in sample D.1, an increase largely at the expense of a marked decline in the basalt count which falls to 7%. (It is uncertain as to why the basalt should decline so markedly yet not the Silurian.)

The count of Carboniferous erratics viewed in the light of all the evidence presented to date, could only reflect Carboniferous bedrock very close to the surface in this area. No hint of this could be gained from any irregularity in the stoss end of the drumlin nor in any immediately apparent change in till in the vicinity, e.g. colour. (The only visible abnormality lay in a marked depression to the west of sample D.14 (Fig. 45a). In part of this depression the soil appeared very stoney, almost gravelly, while nearer the drumlin a very clayey material notably lacking in stones was encountered. These were however probably more explicable in terms of meltwater effects during deglaciation or possibly in post-glacial stream activity.)

Bedrock in such a position could be interpreted as having exerted some control on the location and form of the drumlin. Similar depressions to that encountered here occur elsewhere in the drumlin field, both in the Carboniferous area and in areas to the west where crag and tail or even rock drumlin are encountered. General observations in the Tweed drumlin field also identified several drumlinoid forms, particularly some very large features, in which the stoss ends in particular seemed somewhat irregular, suggestive of bedrock control. This possibility will be discussed more fully in the concluding chapter.

The high Carboniferous count in D.1 is carried on into 8% counts in D.2 and D.5 and 11% counts in D.3 and D.6, thus appearing to fan out from a source in the region of D.1. It would obviously have been desirable to continue this survey east along the drumlin but this was not possible.

Potential contamination from excavations involved in pylon erection stopped sampling short of the drumlin crest and thereafter cropping difficulties intervened. By the time the counts could be resumed again in S.S.14 and the sequence associated with S.S.13, Carboniferous concentrations had fallen to the normal levels of 4%, and below.

CHAPTER SEVEN

HEAVY MINERAL ANALYSIS

Introduction

The stone-counts discussed in previous chapters were concerned with the origins of those till materials down to a minimum size of about 100 mm. Below this size range the only information presented to date has concerned particle size analysis. While patterns and trends in this have been discussed (chapter 2) these are less specific or conclusive in indicating the origins of such material than a petrological or mineralogical observation might be. Accordingly, the heavy mineral analyses discussed in this chapter are intended to augment and complement the particle-size and stone-count studies. Samples examined were S1, S4, S10, S15, S23, S28, S30, S31, S32, S34, S38, S42, SG1 and SG5 from the "basal" series. The locations of these can be observed on Fig. 12.

Methods of preparation and study

The till samples were disaggregated and dried in the laboratory as described in chapter 3. The dried till was then seived and the fraction under 2 mm diameter taken for study. 50 gms were weighed out and to this was added 100 mls of a 4% solution of sodium hexametaphosphate. This was then placed in a stirring flask, made up with de-ionised water and then stirred for at least 10 minutes. After further sieving (-72 + 200 mesh sieves), the residue were washed thoroughly with de-ionised water and then dried. (The coarse residue can be retained for study under the binocular microscope if desired. Large quantities of quartz and felspar grains appear to dominate this.)

The finer residue were then placed into a liquid of high specific gravity, in this case symmetrical tetrabromoethane (S.G. = 2.95), in separating funnels. These were then shaken carefully and left for at least five minutes. The liquid was then drained into centrafuge tubes (c.6 per sample) carefully filling each to exactly the same level. These were then spun at 3000 r.p.m. for five minutes, to assist precipitation and concentration of the fraction heavier than specific gravity 2.95. After removing the tubes from the centrafuge the light minerals were carefully drained off using a simple plug device inserted in the narrow waist of the centrafuge tubes. Holding this plug in place it was also possible to wash the top of the tube thoroughly with acetone to remove all traces of the light minerals. On removing the plug, the remainder of the liquid containing the heavy minerals was poured into a filter funnel (No. 1 paper). Again the tube was washed thoroughly with acetone to remove all minerals. The residue held in the filter paper was finally washed with a little petroleum spirit before being dried and stored in small glass tubes. For study under the polarising microscope temporary slides were made using clove oil (refractive index 1.535) as the mounting medium.

The average number of grains counted was 193 with a maximum count of 304 and a minimum of 150. Most were between 150 and 200.

Before attempting to discuss possible till origins from the results of heavy mineral analysis it is obviously important to know something of the heavy mineral assemblages of the various rock groups concerned. As was suggested in chapter 1, information of this type on the geology of the area is very limited. Possibly the best source in this instance is the Soil Survey Memoir for the country around Kelso and Lauder (Ragg et al., 1960) which contains the results of heavy mineral analyses carried out on the 'C' horizons of many soils. Certain of these soils lie very close to bedrock and are dominated by local rock. The Silurian soils in particular will have limited contamination by other material due to its great extent in the up-ice direction. Elsewhere the very shallow soils developed close to local bedrock will have a minimum of contamination at these lower levels.

Admittedly, important differences do exist between this 'C' horizon and the tills found at greater depths (in which the author's heavy mineral analyses were carried out). This is significant in the possible differing compositions of tills at different levels and also in the varying rates of solution of the minerals due to drainage or textural differences in the till or soil. Accepting these qualifications however, the results of the 'C' horizon analyses in these soils of essentially local derivation will give a guide to the heavy mineral groupings which might be expected within different geological areas.

The Silurian Soils Chlorite, biotite and muscovite appear particularly frequently in soils on Silurian rock. Biotite and chlorite range between 15% and 30% while muscovite along with augite, is generally in the range of 7-15%. Horneblende and zircon may contribute up to about 7%, garnet a little less, and the remainder is made up of small quantities (under 1%) of rutile, tourmaline, epidote, hypersthene and olivine. Ferrous oxides average up to 30%. The above results are based on studies in the 'C' horizons of soils of the Linhope series which have developed on shattered Silurian bedrock.

The Old Red Sandstone soils In soils developed on Old Red Sandstone bedrock, mainly those of the Hobkirk Series and to a lesser extent the Cessford series, garnet and chlorite are particularly prominent. Ferrous oxides reach as high as 50% in these soils while augite, biotite, chlorite, garnet and horneblende are found in concentrations of 7-15%. Muscovite and zircon lie just below this level. Tourmaline (2-4%) and epidote (1-2%) are other minor constituents with small quantities of rutile, apatite, hypersthene and olivine making up the remainder of the count.

In the Cessford series there tends to be more zircon but less garnet than in the Hobkirk Series. The soils of the latter series are generally closer to bedrock.

<u>The soils of the basalt lavas</u> Higher percentages of the ferromagnesian silicate minerals characterise the soils of these basalt lavas of lower Carboniferous Age. In the Darleith Association, it is the soils of the Darleith Series which are developed purely from the lavas and their mineralogical composition is thus of significance in this instance. Augites, along with ferrous oxides, tend to dominate counts, being in the region of 15-30%. Biotite, hypersthene and olivine follow in the range 7-15% with apatite and zircon next in order, contributing up to 7% each. Horneblende contributes only up to 4%, a markedly small amount in view of later findings of the author. Rutile concentrations are of the order of 1-2% while chlorite, epidote, garnet, muscovite and tourmaline each contribute less than ½%.

<u>Soils of the acid intrusions</u> Soils of the Bemersyde series are developed close to bedrock over the various acid intrusives described in chapter 1. These thin soils tend to be dominated by ferrous oxides, augite and biotite (15-30%) with muscovite in the range below this (7-15%). Zircon contributes up to 7%, epidote and garnet up to 4% each, tourmaline 1-2%, while chlorite, horneblende, olivine, hypersthene and rutile each contribute less than ½%.

<u>The Carboniferous soils</u> Heavy mineral assemblages of the lower Carboniferous sedimentaries, lying east of the basalt lavas, are very similar to those of the Old Red Sandstone sedimentaries described previously. More often over the Carboniferous area however, soils are far removed from bedrock and appear to be derived from diverse parent materials. This is one of the major factors to be considered in the examination of the author's heavy mineral studies,

The results of heavy mineral analysis

Fourteen samples of the "basal" till series (chapter 3) were taken for heavy mineral analysis of their fine-sand fractions and the results of these are indicated in Fig. 46. It is proposed initially to examine the occurrence of individual minerals or mineral groups and to discuss the variation in each over the range of samples studied. The relationship of each sample to bedrock type is also illustrated in Fig. 46.

The Fe. fraction The dominance of the opaque minerals, the ferrous oxides, is immediately apparent in the results. Counts range from 28% (sample S.38 in the east of Old Red Sandstone area) to 60% (sample S.4 in the east of the Carboniferous study area). The pattern is one of low counts of under 40% over the Old Red area and in three out of four in the basalt area. Concentrations gradually increase eastwards into the Carboniferous area with samples S.28, 23, 15 and 10 in the mid-forties. The maximum counts of 52% and 60% are reached in S.1 and S.4 respectively, i.e. farthest east in the study area. Ragg et al. (1960) found Fe counts of over 30% only in soils of the Old Red Sandstone areas but the reverse appears to be the case here. The most likely source of the extra iron appears to be the basalt lavas since the increase begins on the lavas and increases down-ice. The very high percentages so far down-ice in S.4 and S.1 are more difficult to explain as erratics evidence points to strong Silurian influence in these tills.

In part some error may lie in the process of identification. Samples S.1, S.4, S.10 and S.15 were particularly difficult samples to identify, containing great numbers of grains which appeared both physically and chemically weathered and many of which were badly stained. In a few instances staining may have been great enough to mask completely grain colour or interference colours, causing a mineral to appear opaque. Any error so incurred is unlikely to be of the order of more than 5-10%

FIG. 46 RESULTS OF HEAVY MINERAL ANALYSES

SAMPLE NUMBERS

	SG5	SG1	S42	S38	S34	S32	S31	S30	S28	S23	S15	S10	S4	S1
AUGITE	3·8	3·1	9·6	3·8	12·0	13·7	15·0	16·7	15·1	11·1	6·6	5·2	2·9	7·2
ENSTATITE	1·3	0·6	3·0	1·8	2·0	5·4	1·5	2·5	4·6	2·9	3·2	2·6	0	0·5
HYPERSTHENE	2·1	1·2	2·0	0·5	4·0	2·4	1·0	0·6	1·0	1·0	0·7	1·1	0	1·0
HORNEBLENDE	2·1	1·9	4·5	3·1	9·5	10·3	11·0	12·4	8·7	8·6	2·8	8·4	9·1	7·2
BIOTITE	11·7	16·9	11·6	16·3	10·0	9·8	2·5	11·2	5·1	8·6	9·1	6·8	2·6	7·2
MUSCOVITE	12·9	12·5	6·1	18·8	5·1	5·4	2·5	2·5	3·7	2·9	11·3	7·3	3·6	8·6
APATITE	1·3	0·6	3·0	2·5	3·0	4·4	5·0	4·3	1·8	2·9	2·1	4·7	3·6	2·4
CHLORITE	3·0	1·2	0	7·3	0	0	0	0	0	1·4	0	0	0	0
EPIDOTE	1·3	0	1·0	0	1·0	0	0	1·9	0	1·0	3·9	2·1	0	0
GARNET	5·6	11·3	8·1	3·8	5·5	4·9	1·0	3·1	5·6	3·9	1·8	2·6	4·7	3·8
RUTILE	1·3	0	0	0·5	1·0	1·0	2·5	0·6	0	0	0	0·6	0·7	1·0
TOURMALINE	7·4	6·9	1·0	1·2	0·5	0·5	1·0	0·6	1·0	2·4	0	0·5	1·4	1·0
ZIRCON	5·6	11·3	8·1	8·5	2·5	2·4	4·0	3·0	3·7	2·9	4·6	7·3	8·4	3·4
FERROUS MIN.	37·0	28·5	37·4	28·0	40·0	32·9	50·0	38·0	45·7	46·5	46·9	44·8	60·0	52·0
UN-IDENTIFIED	3·5	4·5	3·5	4·3	5·0	4·9	3·0	0	3·7	2·4	6·4	5·8	2·9	4·8
OLIVINE	0	0	2·4	0	6·7	2·9	0	0	0	0	0	0	0	0
GEOLOGY (NOT TO SCALE)	Old Red Sandstone				Basalt				Carboniferous					

(BASALTS UP - GLACIER)

Obliquely down-glacier

STONE COUNT RESULTS

	SG5	SG1	S42	S38	S34	S32	S31	S30	S28	S23	S15	S10	S4	S1
SILURIAN	56	8	20	40	18	21	22	24	34	67	53	69	65	71
OLD RED.	26	89	65	40	2·8	18	4	16	4	3	0	3	0	0
CARBONIF.	0	0	0	0	0	0	0	1	5	6	15	10	4	9
BASALT	12	2	11	5	76	59	54	44	51	20	22	8	15	8

ALL RESULTS ARE EXPRESSED AS PERCENTAGES.

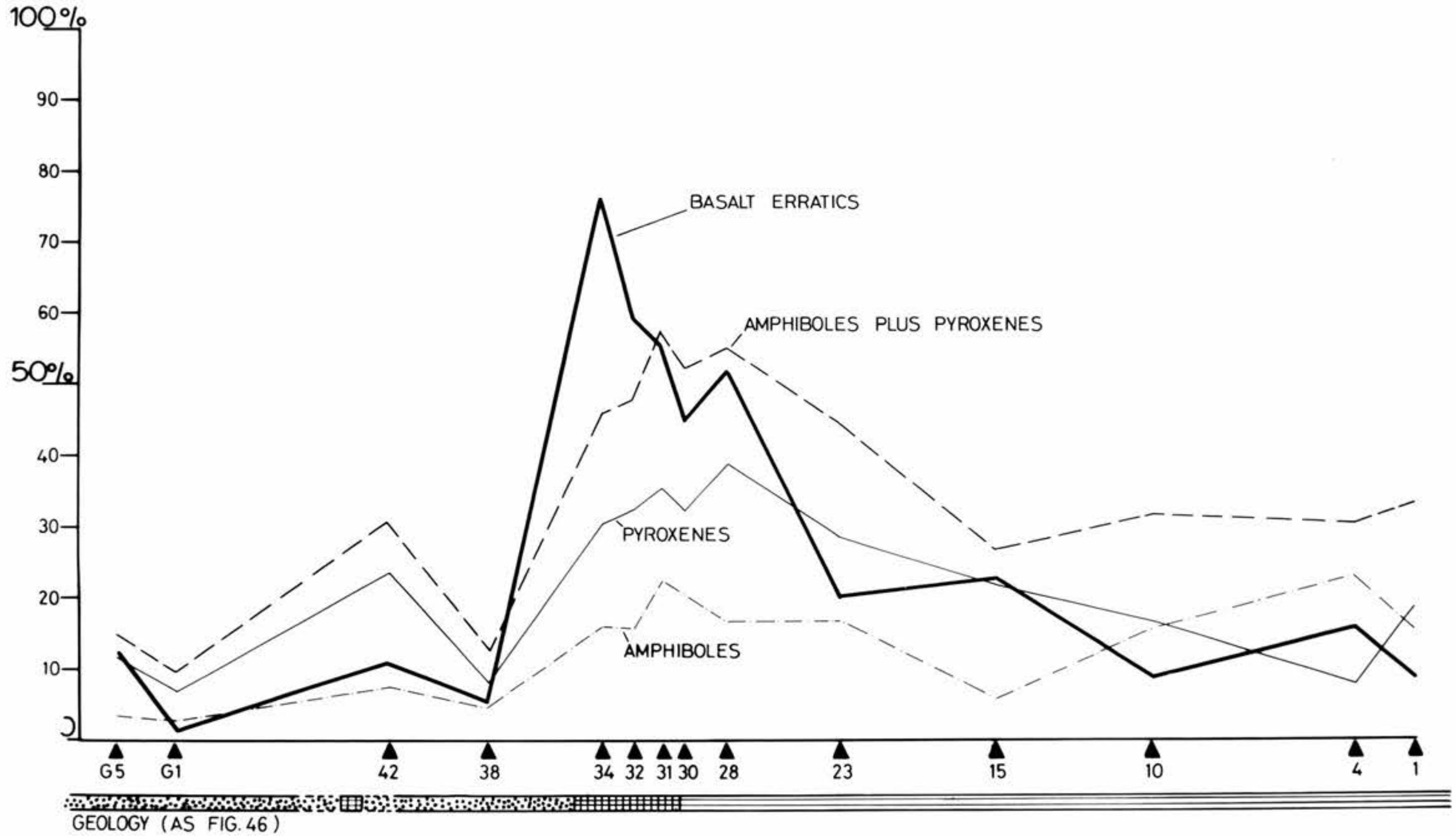
at the most however.

With the known abundance of Silurian erratics in these down-ice samples, the Silurian area must also be considered for explanation of these extra ferrous oxides. Ragg's findings did not suggest the Silurian area as yielding these extra minerals however and the author's results in the Old Red Sandstone area appear to support this. The information on the mineralogy of the Silurian strata is insufficient to permit firm conclusions on this point however.

The Pyroxenes The pyroxenes encountered were enstatite, hypersthene and augite with the latter being particularly prominent. A pattern is more apparent and explicable. The pyroxenes, augite in particular, show a pattern related very specifically to the occurrence of basalt bedrock. Fig. 47 compares pyroxene concentrations with those of basalt erratics in the samples examined. Over the Old Red Sandstone area where basalt influence is less, augite influence does not exceed 3.8% except in one sample (S.42). This sample lies on the southern (down-ice) slope of the East Gordon ridge, an arm of the Kelso Lavas running west from near Greenlaw (Fig.2). (S.42 lies above Old Red Sandstone bedrock.) Augite reaches 9.6% in S.42 and enstatite and hypersthene also show larger counts relative to their concentrations elsewhere in the Old Red area.

Onto the basalt bedrock area itself counts of augite rise to a maximum of 16.7% in S.30, just on the down-ice limit. The delay in this peak (Fig. 47) until this point contrasts with the peak in the basalt erratics which are falling slightly by this stage having been at a maximum on the highest parts of the ridge. Such a pattern is not unexpected however and can be explained as due to the gradual attrition of basalt erratics in transit having provided increasing material in the fine-sand fraction, the peak in the latter occuring down-ice of the erratic peak.

FIG. 47 GRAPH COMPARING COUNTS OF BASALT ERRATICS WITH COUNTS OF AMPHIBOLES & PYROXENES.



Down-ice again onto the Carboniferous bedrock area, augites remain at a higher level than that encountered over the Old Red Sandstone area, falling below 5% only in S.4 (where horneblende is high and the 60% count of ferrous oxides was recorded).

Counts of enstatite and hypersthene also increase to their maximum proportions over the basalt area although they are generally under 5% Enstatite remains quite prominent over parts of the Carboniferous area but gradually falls off with distance from the basalt. Hypersthene declines very quickly to under 1% over most of the Carboniferous area.

The physical appearance of the augite grains was not uniform over all the samples studies. Most augites on the Old Red Sandstone and basalt bedrock areas were angular fragments, physically very broken but chemically quite fresh in appearance and giving bright interference colours. From sample S.28 to S.1 however the augites appear increasingly stained and a little less angular in appearance. Interference colours were often almost completely masked and identification became increasingly based upon other evidence, e.g. the angle of extinction.

The Amphiboles Horneblende was the only member of the amphibole group to be represented in counts. Others, such as riebeckite (from the acid intrusions in the Earlston-Melrose area) might have been expected but none were found in the samples examined. Horneblende is a fairly common detrital mineral derived usually from igneous rocks and, as with the pyroxenes, the concentration of horneblende, in the heavy mineral fraction relates closely to the occurrence of igneous (in this case, basaltic) bedrock (Fig. 47).

The tills of the Old Red Sandstone area contained 1-3% of horneblende, except in sample S.42 where 4.5% was recorded. This slight rise, noted previously for the augites in this sample (9.6%), again appears due to the influence of the basalts from the East Gordon ridge. Horneblende concentrations rise markedly in the tills overlying the basalt bedrock. From 9.5% in S.34 counts rise steadily down-ice to 12.4% in sample S.30 on the down-ice limit of the basalt. Eastwards again, onto the Carboniferous bedrock area, horneblende concentrations remain in the region of 7-9% falling below 7% only in sample S.15 (2.8%). The reasons for this local fall are not immediately apparent.

Such results in the horneblende counts appear to contradict the findings of Ragg et al. (1960). In the 'C' horizons of soils of the Darleith series (developed on the basalts) only 2-4% horneblende was recorded. The results outlined above and illustrated in Fig. 46 and Fig. 47 clearly indicate the basalts as the major source ofthe horneblende. Horneblendes from the Carboniferous, Old Red Sandstone and Silurian areas, especially the latter, no doubt also contribute to the maintainence of this high count in tills overlying the Carboniferous area however.

Many of the horneblende grains identified were of the variety referred to as basaltic horneblende which has red-brown tints, generally showing very marked pleochroism. Amounts of this variety varied considerably but according to no immediately recognisable pattern. Samples S.32, 30, 28 and 23 all contained over 30% of the basaltic variety with a maximum of 38% in S.23, (i.e. 38% of horneblende total). Many other samples had over 20%. Otherwise, greenish varieties of horneblende were most common. Many of the horneblendes did show staining and a masking of interference colours and, though generally not as bad as the augites, this did appear worse in samples further down-ice on the Carboniferous area.

<u>The Micas</u> Biotite and muscovite figure prominently in most of the heavy mineral counts made by the author. Over the Silurian, Old Red Sandstone and basalt bedrock areas, Ragg's findings suggest a clear dominance of biotite over muscovite but in the till samples studied here this was not the case. In general, although biotite did tend to be

dominant, differences were small.

On the Old Red Sandstone area biotite ranged from 11% to 17% while muscovite ranged from 6% to 18% (Fig. 46). Onto the basalt bedrock area muscovite fell markedly to 2.5% and biotite was dominant, maintaining a level of about 10% (except in an abnormally low count of 2.5% in S.31). Down-ice onto the Carboniferous area, differences between the two were nowhere great although moving farther east muscovite appeared gradually to assume dominance. Counts over the Carboniferous area ranged from 3 to 11%.

Potentially all the major geological groups may supply biotite or muscovite to the tills of the basin and it is therefore difficult to draw inferences from mica concentrations. However, the relative lack of large concentrations of mica, in the Carboniferous area, compared to the greater proportions noted in the Old Red Sandstone area, may perhaps be taken as further evidence to indicate lack of Carboniferous contributions to the upper levels of these very deep tills. Considerably more dilution of "local" erratic material may be envisaged in the Carboniferous area with the greatly increased deposition noted there.

Chlorite, which according to Ragg <u>et al</u>. (1960) figured prominently in soils of Silurian origins in particular, was nevertheless lacking in most samples examined. In only 4 samples was chlorite identified. Samples SG5, SG1 and S.38 in the Old Red area gave 3%, 1.2% and 7.3% chlorite respectively. Sample S.23 in the Carboniferous area gave 1.4% chlorite. Such isolated results, particularly the 7.3% in S,38 are difficult to explain since results of other minerals were on the whole reasonably applicable to an overall pattern.

<u>Garnets</u> Garnets are ubiquitous detrital minerals, derived in this instance from the sedimentary rocks of Old Red Sandstone and Carboniferous ages and also from the Silurian sediments particularly those of

argillaceous type such as the shales and mudstones.

Garnets were most common in the tills of the Old Red Sandstone area, a maximum count of 11% being registered in S.G.1. Other samples generally yielded 5-10%. Onto the basalt bedrock area garnets fell below 5% and indeed as low as 1% in sample S.31. Onto the Carboniferous area, garnet counts generally stayed under 5%.

The high counts in the Old Red bedrock area offer only two potential sources for the garnets, i.e. the Old Red Sandstone bedrock itself or the Silurian area to the west. Ragg's findings clearly indicate the Old Red Sandstone as the major source but equally Silurian contributions are significant. The lower garnet percentages in the Carboniferous bedrock area, with the known Silurian influence in this area, again suggest little contribution from local bedrock in terms of heavy mineral assemblages. The Old Red Sandstone and Carboniferous sediments are believed fairly similar in composition, (Ragg et al., 1960) and Carboniferous contributions in this area might have been expected to raise garnet concentrations to the order of 5-10% in this area.

No attempt was made to record individual types of garnet but in general two distinct varieties were noted. One variety exhibited very clearly a sub-conchoidal fracture system in a generally rounded overall form. The other was a characteristically pitted, sieve-like surface, again on a generally rounded grain. Both are frequent in Silurian strata (Dr. J.A.T. Young, pers. commun.). A variety of colours was noted but browns or red-browns were common in those with a clear fracture system. As with so many other minerals, many of the garnets were quite altered in appearance, particularly farther east into the Carboniferous area, and staining was frequent.

Zircon Zircon behaves very similarly to the garnets in the tills examined here, with high counts in the Old Red Sandstone bedrock area and low counts over the basalt area. Zircon counts rise to higher levels over the Carboniferous area than was the case with the garnets however.

The maximum count in the Old Red Sandstone area (11.3%) occurs, as did that of the garnets, in sample S.G.1, a sample with 88.8% Old Red Sandstone concentration in the stone count. While relationships between heavy mineral concentrations and erratic concentrations are not quite so simple (e.g. the "delayed peak" in the pyroxenes on the basalt area as described in Fig. 47), this does lead to the suggestion that many of the zircons are derived from the sediments of Old Red Sandstone age. Equally it is known however that the Silurian rocks are also a potential source (Ragg <u>et al.</u>, 1960). The recovery of the zircons in the Carboniferous bedrock area is one of the few lines of evidence supporting potential Carboniferous contribution to these tills.

Many of the zircons noted over the Old Red Sandstone bedrock area, like the garnets, had pitted and often scratched surfaces and a generally rounded although fresh-looking form. Others were of a much higher relief and in these varieties in particular, inclusions were common. (Many of the inclusions were identified as tourmaline.) The zircons of the Carboniferous area, while essentially similar in type, were more difficult to identify because of greater weathering and staining.

<u>Tourmaline</u> Although tourmaline percentages are generally considerably lower than those of garnet or zircon, the pattern of occurrence is broadly similar. In the Old Red Sandstone area counts of 7.4% (S.G.5) and 6.9% (S.G.1) were reached and in these samples very fresh tourmalines were found. Schlorite appeared to be the main variety. Inclusions were common.

Such high counts proved to be exceptions however and down-ice onto the basalt area tourmaline concentrations fall below 1%. A recovery was made only in a few samples on the Carboniferous bedrock area but most were below 2%.

Apatite The major concentration of apatite was found on the basalt bedrock area (3-5%) with generally lesser contribution on the Old Red Sandstone (1-3%) and Carboniferous (1-5%) bedrock areas. Most apatites would have been derived from igneous rocks and the Silurian or the other major sedimentary groups are unlikely to yield apatite in any amount. Apatite is thus seen mainly as an indicator of igneous influence (both intrusions and the lavas) and as such some counts are perhaps surprisingly high.

Epidote Epidote does not figure prominently in any of the heavy mineral counts, the maximum being an abnormally high 3.9% in sample S.15. Highest counts appeared generally in the Carboniferous area while those of the basalt and Old Red Sandstone areas were generally less than 1%. On the other hand nil-counts of epidote were also made in the Carboniferous area and no clear pattern could be assigned to its occurrence.

Rutile Percentages of rutile were small with the major concentration (maximum 2.5%) on the basalt bedrock area. Over the sedimentary areas counts were frequently nil and generally under 1%.

Olivine Results of olivine occurrence are perhaps among the most surprising of all the finds made in these studies. In only two of the samples examined was olivine found. 6.7% was found in sample S.34 and 2.4% in S.42. Sample S.34 occurred in the thin till on the highest parts of the basalt ridge. S.42 lay immediately down-ice of part of the East Gordon ridge and also showed strong basaltic influence as evidenced by the rise in pyroxene and amphibole counts discussed previously (Figs. 46 and 47). Despite the possibility of alteration of much of the olivine in lavas which are often exceedingly weathered (chapter 1), more olivine might have been expected over the basalt bedrock area in particular, Heavy Mineral Assemblages on tills of the Old Red Sandstone area

Having examined the behaviour over the different bedrock areas it is now possible to attempt to summarise these by looking at "typical tills" in these areas. The tills in each geological area will vary, particularly in an east-west direction and additional notes are given to clarify this and other variations. A typical till on the Old Red Sandstone bedrock area would have a composition as below.

Ferrous oxides	28 to 38%
Biotite	10 to 15%
Muscovite	10 to 15%
Garnet	5 to 10%
Zircon	5 to 10%
Chlorite	1 to 7%
Tourmaline	1 to 7%
Augite	up to 4%
Enstatite	under 2%
Hypersthene	under 2%
Horneblende	c. 3%
Apatite	1 to 3%
Rutile	under 1%
Epidote	under 1%

Additional notes: Biotite tends to be slightly dominant over muscovite in any one sample. Pyroxenes and amphiboles in particular might expect to show increased percentages in the vicinity of certain igneous intrusions. Chlorite and tourmaline would vary in concentration but counts of the order of 6-7% were found only on tills of the Old Red Sandstone area and appear thus as fairly reliable indicators if found in quantity. Most minerals in these samples tend to be quite fresh in appearance despite physical breakdown .

Heavy mineral assemblages in tills of the basalt bedrock area

Ferrous oxides	30 to 50%
Augite	12 to 18%
Horneblende	10 to 12%
Biotite	10%
Muscovite	up to 5%

Enstatite	2 to 5%
Hypersthene	1 to 4%
Garnet	1 to 5%
Zircon	2 to 4%
Apatite	3 to 5%
Rutile	1 to 2%
Olivine	0 to 6%
Epidote	under 1%
Tourmaline	under 1%

Additional notes: Augite counts are greatest towards the down-ice edge of the basalts except where tills are very deep. 25% or more of the horneblende might be of the typically basaltic variety. The pyroxenes and amphiboles, alongwith apatite and rutile achieve their maximum concentrations over the basaltibedrock area. The olivine count appears very variable and it is not unusual for none to be found. Many of these minerals, the augites in particular, appear physically very fragmented but otherwise very fresh in appearance.

Heavy mineral assemblages in tills of the Carboniferous area

Ferrous oxides	40 to 60%
Augite	5 to 15%
Enstatite	1 to 5%
Hypersthene	under 1%
Muscovite	5 to 10%
Biotite	5 to 10%
Horneblende	7 to 9%
Zircon	3 to 8%
Garnet	2 to 6%
Apatite	1 to 5%
Tourmaline	1 to 2%
Rutile	under 1%
Epidote	0 to 3 %
Chlorite	0 to 1%

Additional notes: Percentages of ferrous oxides increase towards the east of the study area. Augite concentrations decline slowly from west to east over the range indicated as does enstatite. In the micas, muscovite tends to assume dominance over biotite towards the east of the study area although differences are generally small. All samples but especially those farthest east, show increasing signs of weathering both in the physical attrition of the grains but more importantly perhaps, in the chemical staining of grains. This latter process can greatly complicate heavy mineral identification in samples nearer the down-ice limit of the study area.

CHAPTER EIGHT

ORIENTATION ANALYSES IN TILL MACRO-FABRICS

Introduction

Macro-fabric analysis of lodgement till has long been recognised as an indicator of glacier movement. Holmes (1941) was the first to attempt a real understanding of the technique and its implications. Harrison (1957), Andrews and King (1968), Beaumont (1971) and many others have since developed and applied the study. As a technique it is most useful along with other directional indicators. Beaumont (1971) combined it successfully with stone-counts on the lower till sheet in E. Durham. While the role of orientation analysis as a directional indicator is largely accepted, the actual inheritance of the fabric pattern is less than fully understood.

Holmes showed in particular how size and shape of stones influenced patterns and attempted to explain development of the parallel and transverse peaks. He classified each stone into one of six major forms and categorised the degree of rounding. Results indicated that different stone shapes favoured different attitudes, some parallel, some transverse.

Glen, Donner and West (1957) in their considerations of the possible development of the fabric pattern, suggested three main sources. Firstly there was the method of entrainment in the ice. This is difficult to estimate, and although probably not random, it was thought best to assume so initially. Secondly there are the processes inherent in transportation or flow. Early workers (Jeffrey, 1922; Taylor, 1923) had shown that under laboratory conditions protracted flow tended to produce a transverse peak and Binder (1939) suggested that a long axial ratio tended to produce parallelism. Considerable development of these early ideas has been made by later workers. Thirdly there was the control on fabrics by deposition and subsequent movement.

Harrison (1957) showed the importance of the transportational environment in the inheritance of the fabric pattern. The relevance of these observations has already been suggested in chapter 2, in the fabrics maintained by the melt-out tills lying above sand and gravel sequences (Figs. 15a to 15d). In this context it is notable that the transverse peak, so well developed in many of the author's samples, is suggested as being developed in narrow till bands between ice layers (Boulton, 1972). This supports the theory that much of the Silurian-dominated till is derived from levels high in the basal ice. Not all tills were suggestive of deposition by melt-out however.

<u>Potential errors is fabric analysis</u> While every attempt was made to sample accurately there are potential sources of error.

1. Compass reading were made to the nearest five degrees. It is envisaged that this would cause insignificant errors, since it would tend to even out statistically. Equally since ice flow could well have varied by more than 5 degrees within very short periods, such generalisations are valid,
2. Magnetic errors can arise from metal objects, magnetic boulders and local magnetic anomalies.
3. Error can occur in axis interpretation; it is often difficult to distinguish the major axes of irregularly-shaped fragments.
4. Interference can occur from boulders occurring locally within the till, as in orientation O.S.6 (Fig. 15d, chapter 2).
5. Post-depositional movement of the till may have occurred. The

possibility of flow till (Hartshorn, 1958) or soliflucted till overlying stratified drift in former meltwater channels has already been suggested in chapter 2. Some smaller degree of solifluction may equally have affected samples taken too near the surface.

6. Post-glacial interference of the till may have occurred in a number of ways, e.g. human or animal excavations, plant roots, periglacial activity or slumpage due to collapse or melt-out.

Numbers 4 and 5 might show as discrepancies on plots in some instances yet might approximate closely enough to expected orientations to be undetected as abnormalities in others .

The maximum error in measurements of the type carried out by the author has been calculated at 8 degrees in orientation and 6 degrees in dip by Harrison (1957) and at 5 degrees in both orientation and dip by Andrews (1965). Hill (1968), under laboratory conditions estimated error by any one worker to be under 5 degrees.

Andrews and Shimuzu (1966) suggested that a major source of potential error lay in the approach of one sample/one site and at that time the question of variability within sites had been little investigated. West and Donner (1956) had found variations extending over an arc of 60 degrees in orientation separated vertically by 1.5 m and 4 m in a single till layer some 8 m thick. Young (1969) also examined fabric variability over very short distances. Considerable variation was found within depths of less than 60 cm but lateral variations over similar distances were small in comparison. Kauranne (1960) found essentially similar patterns.

Although the author's samples were taken from similar depths at different sites this does not imply that tills in each sample were deposited contemporaneously. No check was made on variability within sites either lateral or vertical, although the consistency of results over the study area (particularly in relation to local drumlin direction) suggests that variations are small.

Rose (1974) has recently suggested that in many cases involving lodgement till, there is no need for the caution expressed by many workers (Young, 1969, Boulton, 1971 etc.). He suggests that reliable results are obtained using a series of single local samples. Rose qualified his findings with the proviso that before fabrics can be interpretated as directional indicators the processes of deposition must be known. Penny and Catt (1967) point out, for example, that a dominant orientation in a fabric pattern could represent one of at least four alternatives.

1. The direction of movement of parent ice (Richter, 1932).
2. Abnormally enlarged transverse orientation from the parent ice (Donner and West, 1957; Glen, Donner and West, 1957).
3. The 'a' direction of a later re-advance (Mach, and Dreimanis, 1964).
4. The 'b' or transverse direction of a later re-advance (Penny and Catt 1967).

In the current study the local variability of fabric was not investigated since the continuous prescence of a reliable directional indicator (drumlins) acted as an adequate control on results. This study had two primary contributions to make. Initially fabrics were related to stone-count evidence of ice-movement and the processes of sedimentation and secondly to drumlin formation. It was hoped that the fabric patterns might contribute to a study of drumlins themselves as well as allowing comparisons to be made with Wright's (1957) work in Wadena. In the present study there was no real control over the location of sites examined. In particular it would have been desirable to examine more stoss-end sites and to study any one drumlin in detail. Time available for study in any one area was often restricted and in only one instance was a more detailed study possible (orientations 0.14 to 0.19 inclusive)

The method of study

25 fabric analyses were made in association with the pipeline operations described in chapter two, most being on the floor of the trench (2m - 2.40m deep). Loose till was first removed and stones then excavated with a knife. The 'a' and 'b' axes were measured and their suitability for analyses determined: a ratio of at least 3:2 in a:b axes was a minimum requirement. The stone was then carefully replaced in its mould and orientation and dip were measured. Care was taken to remove all metal objects during measurement.

Holmes (1941) used 100 stones per site in his orientation studies. In the present study 50 stones were used, a number that has been shown to be sufficient for meaningful results (Young, 1969). In this instance fabrics were not being used as independent directional indicators and other directional indicators were available. Only one study was made at each site and sites were generally several hundred metres apart (Fig. 48), except in one instance where studies were made 10-12m apart on the stoss end of the Hardacres drumlin (N.T. 743419).

Despite the work of Holmes (1941) and reminders in the study of Andrews and King (1968) in a Yorkshire drumlin site, stone-shape was not measured in this study. Considerable homogeneity was observed, particularly in the high degree of rounding of the Silurian erratics, the major constituent of most of the till. Some were well-rounded rhombohedroid forms (Holmes, 1941) but many tended to be shorter, well-rounded stones, often ovoid or discoid in shape. Basalt fragments were less regular in shape and degree of rounding. Fine striae were observed on two wedge-shaped basalt erratics at two sites. One sample clearly showed these striae in two sets, parallel to the longer sides of the wedge.

The Results

Fig. 48 shows site location and general regional pattern of results.

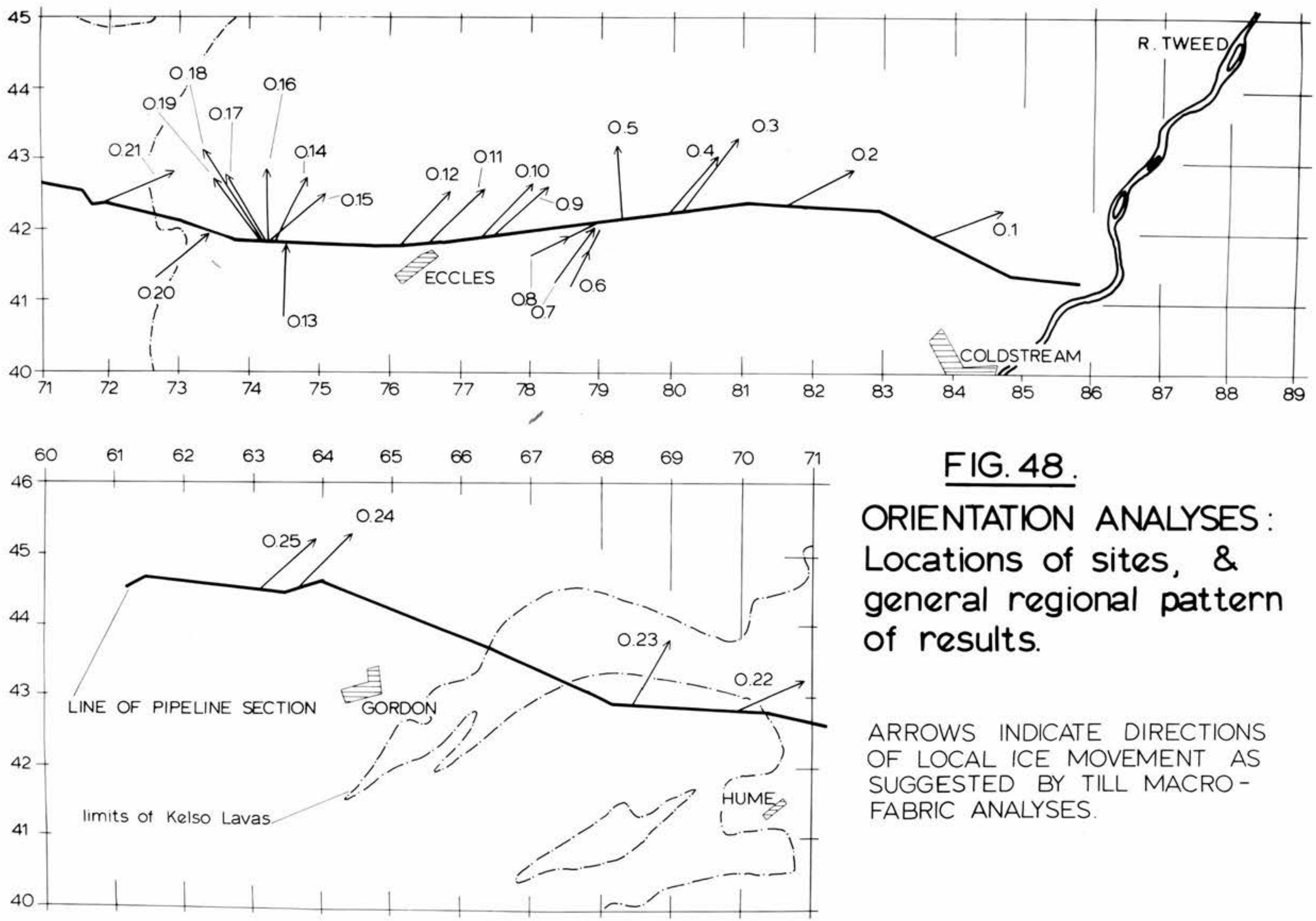


FIG. 48.

ORIENTATION ANALYSES: Locations of sites, & general regional pattern of results.

ARROWS INDICATE DIRECTIONS OF LOCAL ICE MOVEMENT AS SUGGESTED BY TILL MACRO-FABRIC ANALYSES.

Fig. 49 presents all results on polar equidistant projections. Measurements relate to magnetic north. The number of stones in each 10 degree grouping is proportional to the distance of the peak from the centre of the diagram. Local drumlin alignment, preferred orientation derived from vector analysis (Curry, 1956; Young, 1971, pers. commun.) and mean orientation $\left(\frac{\Sigma x}{50}\right)$ are also shown. Standard deviation was calculated for each sample using the formula

$$S.D. = \sqrt{\frac{\Sigma x^2}{n} - \bar{x}^2}$$

where x is the individual sample, $\bar{x}$ is the mean and n is the number of samples (Fig. 50).

Although standard deviation tends to be large it is consistently so and in no way suggests results to be irregular. (Standard deviation of the S.D. values themselves was only 8.2° despite one or two abnormally low values in fabrics with well developed parallel patterns.) The large values for standard deviation are a result of well-developed transverse orientations (as in samples O.7, O.14 etc.) although in a few cases they relate to more confused patterns (e.g. sample O.5). Fig. 51 illustrates this point. The visual impression of Figs. 48 and 49 clearly supports the idea of a single till sheet deposited by ice flowing from the west and south-west.

Fig. 50 indicates the strength of the parallel and transverse peaks expressed as percentages and Fig. 52 illustrates this graphically. (An apparently weak orientation visible in O.5 in Fig. 49 is now clearly seen to dip strongly out of the drumlin suggesting some disturbance during melt-out or subsequent till movement.)

The stones in the transverse peak varied from 22% to 56% with a mean of 35.7%. This represents a strong transverse alignment. 64.3% of stones were found to trend within 40 degrees of the mean or preferred orientation. Within this group, seven samples showed a dominant down-ice dip and seventeen dipped up-ice. Those with pronounced downstream dip

FIG. 49. GRAPHICAL PRESENTATION OF FABRIC ANALYSES.
(Polar equidistant projections.)

Part 1 : Orientation Studies 1 - 12.

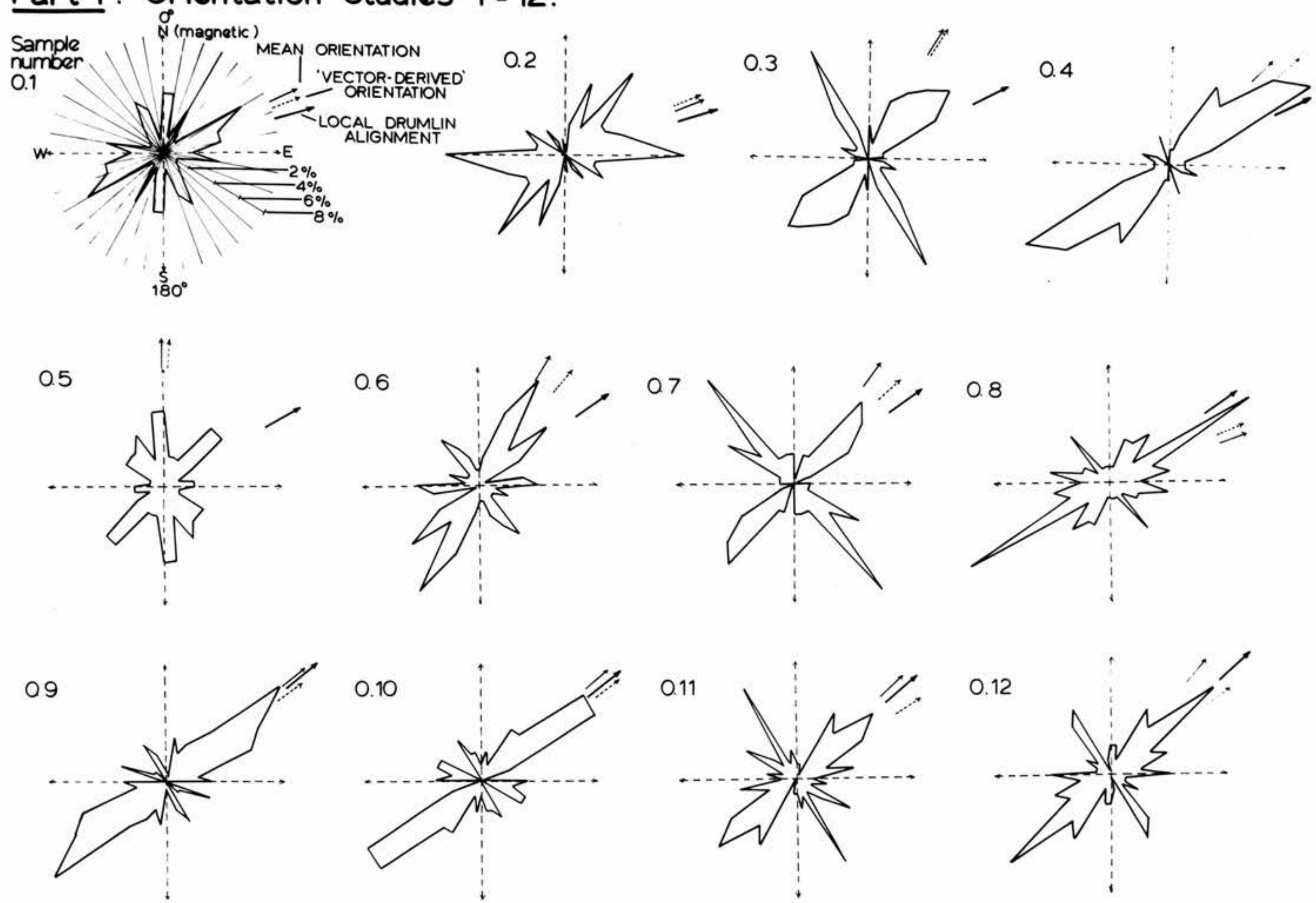
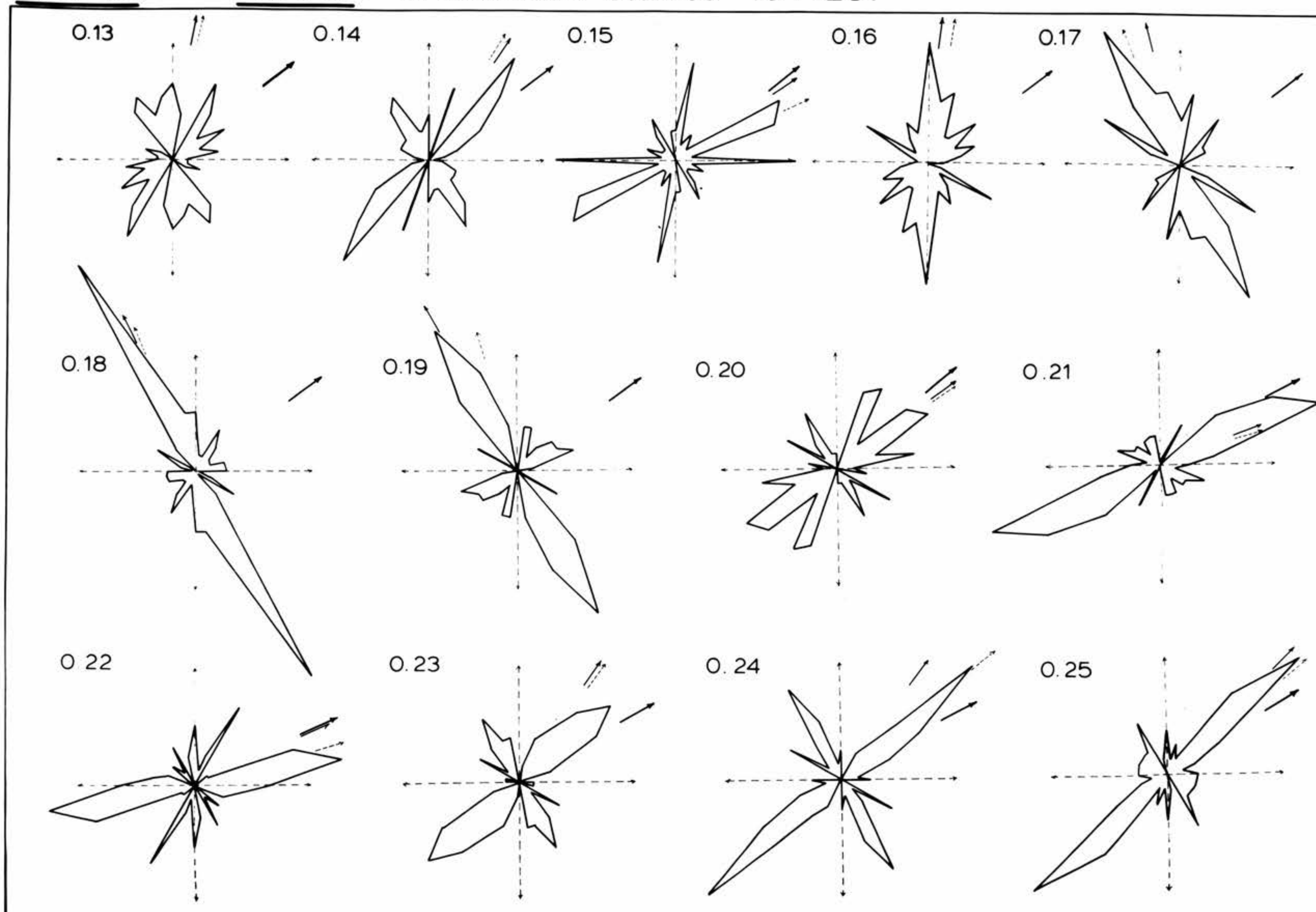


FIG. 49. **Part 2** : Orientation studies 13 - 25.



FIGS. 50 & 51.

FIG.50 ORIENTATION ANALYSES :

DIRECTION OF DIP ; STANDARD DEVIATION.

sample no.	% with up-ice dip 80° arc	% with down-ice dip 80° arc	% dipping transv. 2 × 100°	standard deviation
1	23	29	48	50
2	42	36	22	37
3	26	34	40	44
4	56	22	22	18
5	no	preferred	orientation	51
6	21	44	38	36
7	19	25	56	55
8	53	17	30	24
9	50	24	26	35
10	32	31	37	40
11	45	12	43	48
12	38	31	31	46
13	17	27	56	50
14	44	10	46	48
15	31	27	42	44
16	30	36	34	43
17	34	42	24	35
18	49	23	28	39
19	42	30	28	46
20	39	29	32	44
21	49	29	22	38
22	38	31	31	49
23	30	30	40	44
24	31	27	42	48
25	41	19	40	44
	MEAN 36·7	MEAN 27·6	MEAN 35·7	MEAN 42·2

FIG.51. GRAPH OF CORRELATION BETWEEN STANDARD DEVIATION AND THE TRANVERSE FABRIC STRENGTH.

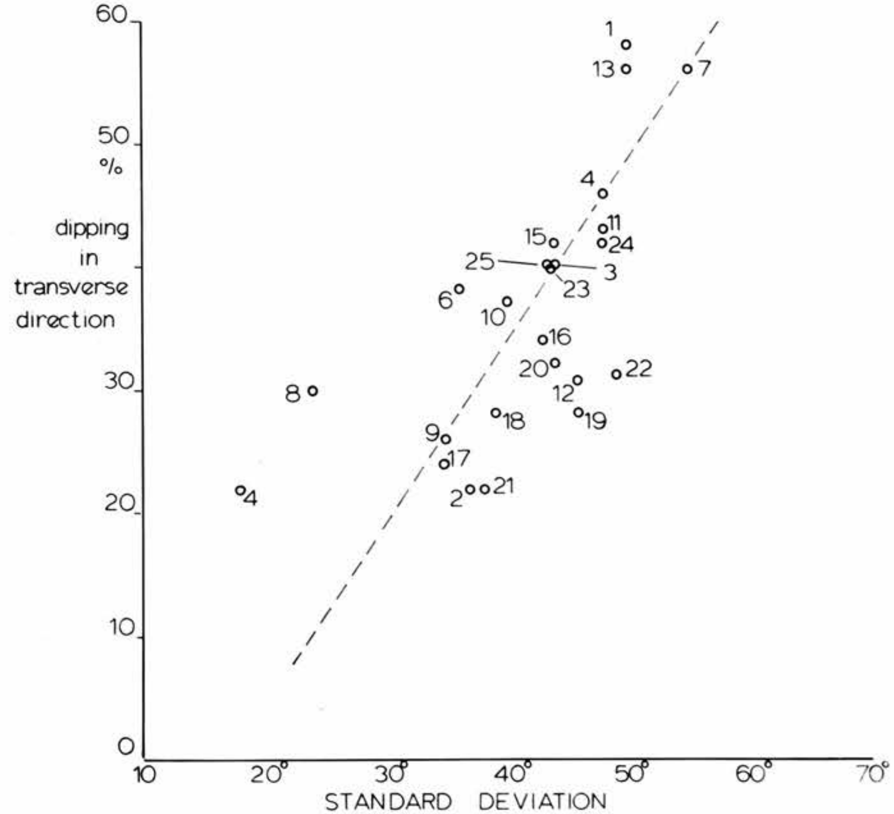


FIG. 52 ROSE DIAGRAMS OF TILL FABRICS - SHOWING DIP DIRECTIONS.

Part 1 : O.1 - O.12

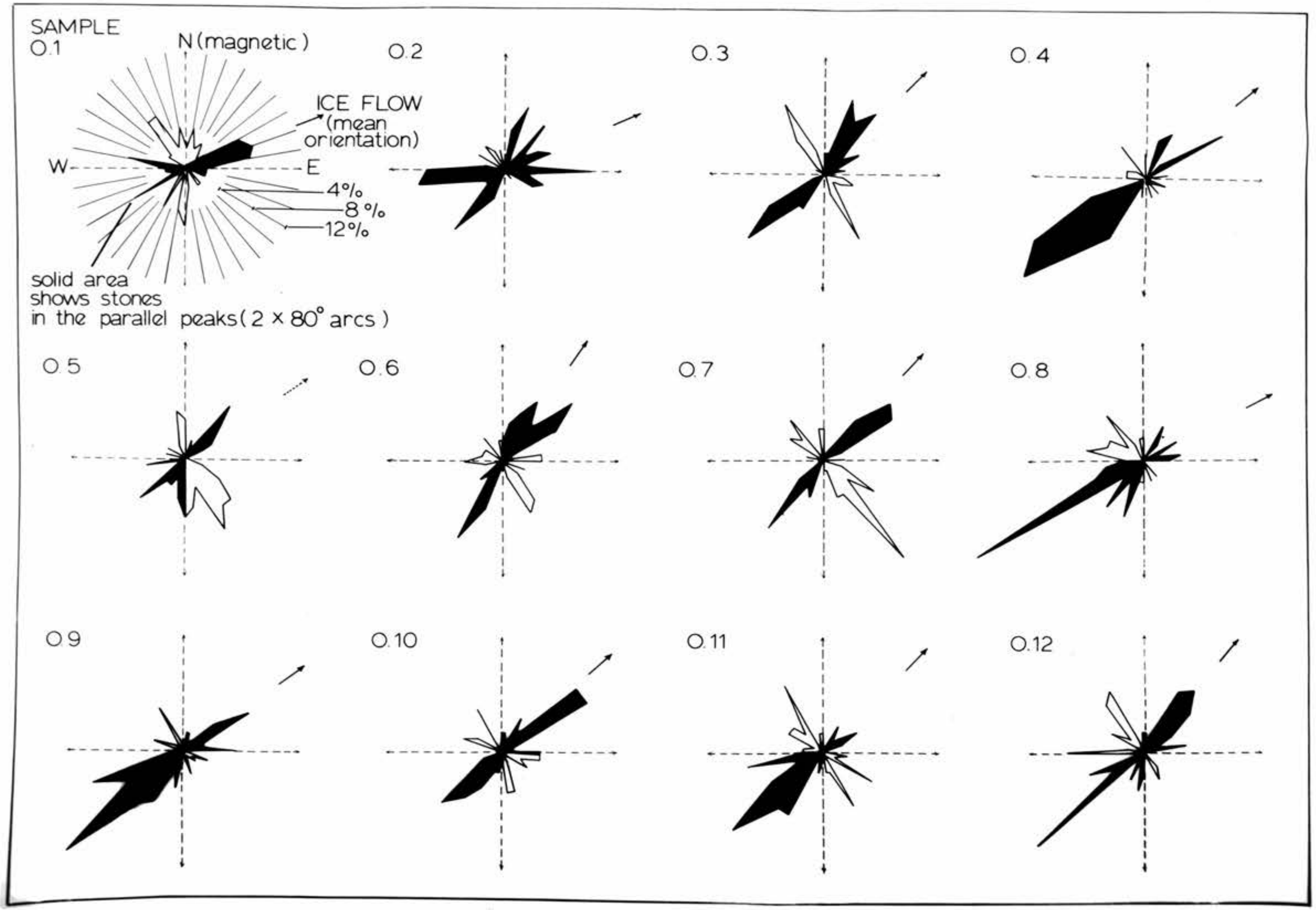
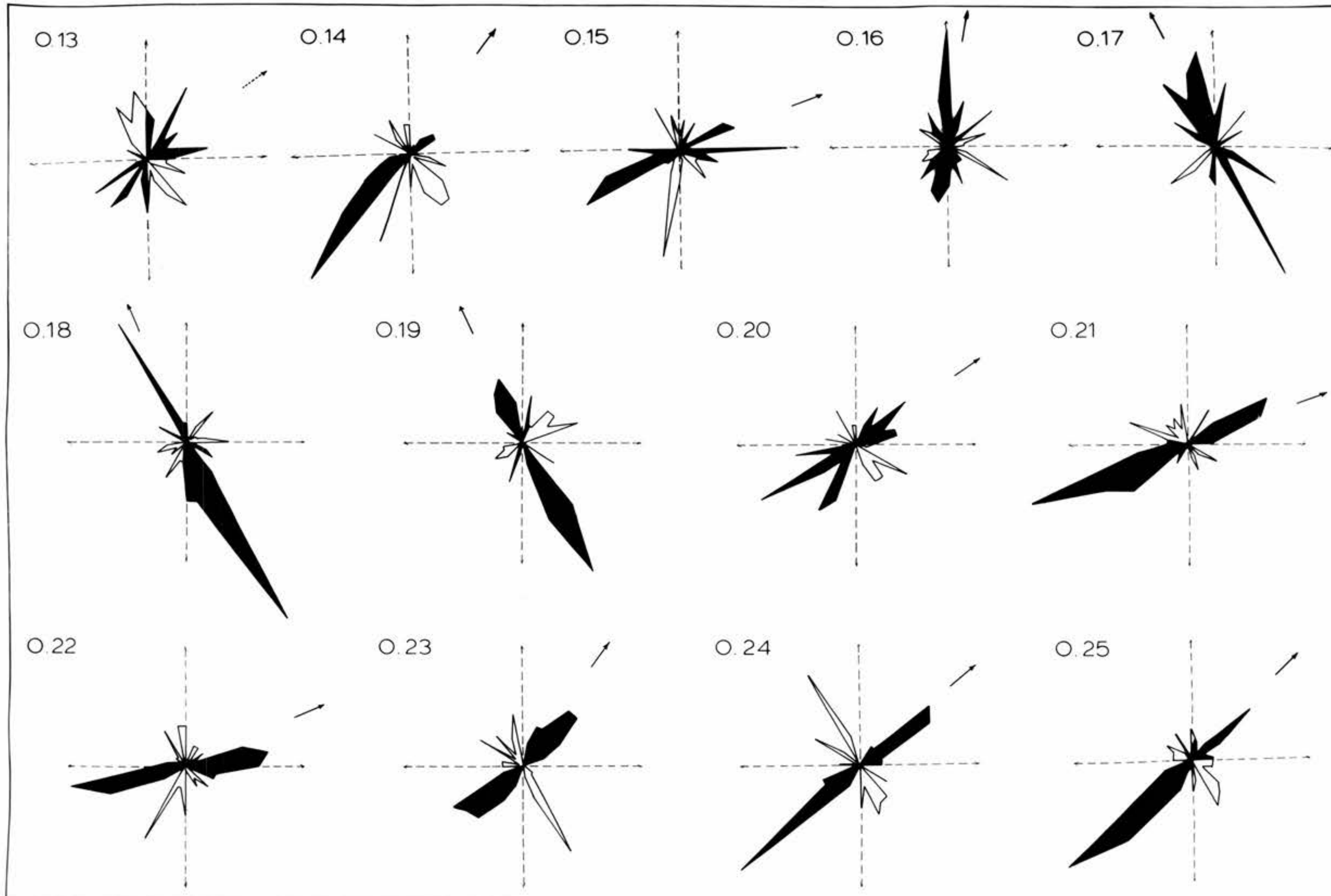


FIG. 52. **Part 2** : O.13 - O.25.



FIGS. 53 & 54.

FIG. 53 Angles of plunge of stones.

D SITES WITH PREFERRED DOWN-GLACIER DIP.
S STOSS-END SITES.

SITE NUMBER		NO. OF STONES DIPPING 10° OR LESS.	NO. OF STONES DIPPING 15°-35° INCL.	NO. OF STONES DIPPING 40° OR MORE
1	DS	74	24	2
2	S	62	32	6
3	D	78	18	4
4		72	26	2
5		56	32	12
6	D	64	32	4
7	DS	60	38	2
8	S	44	48	8
9		46	40	14
10		50	42	8
11		52	46	2
12		34	52	14
13	D	50	48	2
14	S	76	24	0
15	S	58	42	0
16	DS	62	36	2
17	DS	50	40	10
18	S	58	40	2
19	S	80	18	2
20		64	34	4
21		58	32	10
22		76	20	4
23		76	14	10
24		76	20	4
25		66	34	0
		MEAN :61·7%	MEAN 33·3%	MEAN 5·1%

FIG. 54 A comparison with Wright's (1957) work in the Wadena drumlin field.

A : DIRECTION OF PLUNGE.

	% DIPPING UP GLACIER	% DIPPING DOWN-GL.	% DIPPING TRANSVERSELY
WRIGHT	64	27	9
TWEED AREA	36·7	27·6	35·7

B : ANGLE OF PLUNGE

	% DIPPING 10° OR LESS	% DIPPING 15°-35° INCL	% DIPPING 40° OR MORE
WRIGHT	34	66	
TWEED AREA	61·7	33·3	5·1
		38·4	

tended to develop slightly stronger transverse orientations (mean of 42.3%) compared with those dipping up-ice (mean of 32.9%). The significance of this is not fully understood but its relevance to drumlin form is considered later.

The angle of plunge was also measured and results are shown in Fig. 53. An average of 61.7% of stones dipped 10 degrees or less from the horizontal. 33.1% dipped at between 15° and 35° inclusively with 5.1% dipping 40° or more. No significant difference was detected between sites with a pronounced upstream dip and those with a dominant downstream dip. Sites with well-developed transverse peaks showed a slight tendency to lower angles of dip but results were not conclusive.

A comparison with Wright's (1957) work in Wadena

The only other major areal study of fabrics in a drumlin field is that of Wright (1957) in the Wadena drumlin field, Minnesota. Wright's study involved sixteen analyses at fourteen sites and approximately 50 stones per site were measured. Controls on size and axes ratio were similar to those used by the author.

Wright's results indicated a strong preferred orientation parallel to the line of the particular drumlin sampled. A marked upstream dip was observed. On some diagrams a minor transverse pattern was evident but on average only 9% of stones were aligned transversely. These results differ considerably from those of the Tweed drumlin field (Fig. 54). Apart from obvious differences in the strength of the parallel and transverse peaks, Wright's fabrics also show a much stronger preference to an up-ice dip in the parallel peak. Considerable discrepancies are also noted in the amount of plunge recorded (Fig. 54). While almost 62% of stones in the Tweed drumlin field dipped at 10° or less, only 34% of those examined by Wright did so. Wright suggested that his results in Wadena, particularly the up-ice plunge and the moderate (rather than gentle) plunge angles, were particularly related to the ice conditions necessary for drunlin formation in the Wadena field. While this may have been thee case in Wadena, the final stages of drumlin formation in the Tweed area did nor produce similar fabrics. The drumlins described by Wright in Wadena differ slightly from those of the Tweed in area in being lower on average and with a tendancy to a symmetrical profile. Side slopes were of a low angle (under 3°) while steeper-sided examples were recognised in the Tweed area. Fabric patterns apparently suggest different ice conditions during their formation.

Wright's claim for the individuality of this fabric pattern came from comparison with three other major studies of till macro-fabrics. The first was the study by Holmes (1941) in ground moraine in New York State, the second by Hoppe (1952) in dead-ice moraine in Sweden, and the third by Donner and West (1956) in the ground moraine of three tills in East Anglia. As the following table illustrates the author's results appear more closely related to those of Donner and West than to those of Wright.

	% dipping 10° or less	Average plunge	Up-ice	Down-ice	Total in parallel	Transverse peak %
WRIGHT	34	23°	64	27	91	9
HOLMES	74	11°	No distinction made			
HOPPE	77	10°	Not related to ice flow			
DONNER AND WEST	64	14°	35	46	81	19
TWEED RESULTS	62	13°	37	28	65	36

Major differences from Donner and West clearly lie in the strength of the transverse peak in the Tweed fabrics and in the dominant down-ice dip of the East Anglian fabrics. Percentages dipping up-ice are similar but the Tweed results show an average of 16% less in the parallel direction.

INTERPRETATION OF THE TWEED DRUMLIN FIELD FABRICS

Before interpretating the results, certain qualifications must be made.

The deepest sample studied was c. 2.40m from the present surface yet in parts of the Tweed basin till depth is measurable in tens of metres (chapter 1). The depth of till over most of the study area is generally believed to be less yet, in considering the relevance of the fabrics to drumlin form, samples discussed here represent only the upper 2 m to 2.5 m of till on any drumlin.

Studies outlined in chapter two have already indicated the presence of melt-out tills, and sands and gravels to at least 2.40m in depth in some areas. During sampling care was taken to avoid obvious areas of potential melt-out fabrics (except those discussed in chapter two). The fabrics examined, although at similar depths are not necessarily of contemporaneous deposition nor from similar transportational and depositional environments. All samples were in tills that appeared very compacted and from which stones were often difficult to extricate. The limited scope of the study in terms of choice of position on drumlins has already been suggested, but the limited opportunity to sample at greater depths was more regrettable.

Not all samples show clear preferred orientations and some possible reasons have been suggested. In fabrics examined here the major discrepancies may be the result of movement during or after deposition. Equally the presence of so many well-rounded Silurian erratics and irrefularly shaped basalt fragments may have contributed to the weakness of some fabrics either in their failing to maintain a preferred orientation during transport (due to insufficient elongation), or in sample error due to difficulties of axis identification. Melt-out tills may also exist to a greater extent than is at first apparent and the angle of dip will be suggested as possibly indicating this.

THE DEGREE AND DIRECTION OF DIP

The Tweed results (Figs. 50, 52 and 53) show 64.3% of stones trending in the parallel direction, dipping at gentle angles (62% at 10^0 or less), and with a preference to an upstream dip. The recent literature presents often conflicting views regarding the interpretation of such results and in particular their significance in relation to Wright's (1957) findings. Wright suggested that his results, showing higher angles of plunge and more pronounced up-ice dip, might be the consequence of upward rising shear planes in the basal ice. He saw spreading and thinning of active ice over a great distance as explaining the Wadena fabrics, with flow lines yielding a pronounced up-ice dip in the manner envisaged by Demorest (1943) in his theory of obstructed extrusion flow. While there is evidence (chapter two) of widespread stagnation of ice in the Tweed basin there is no evidence of marginal thinning and spreading of the ice sheet as was envisaged by Wright in Wadena. The irregular topography in the Silurian area, in the Old Red Sandstone area with its many intrusions, and over the basalt ridges would produce active shearing in the basal ice, but there is no evidence of such a fabric being maintained during deposition. Subsequent discussion (chapter nine) of erratic patterns on the tail of Black Hill (G.R. NT 585370) suggest very active and turbulent basal ice in this area. The degree of dip of the fabrics examined appears to support the ideas expressed previously in relation to stone counts, i.e. that the tills are derived from parallel debris bands higher in the basal ice and subsequently let down as the ice thinned and ultimately stagnated <u>in situ</u>. It is also possible that dip angles have been altered during deposition without any disturbance of arrangements in the parallel plane. Glen, Donner and West (1957) suggest that the orientation of long axes in the parallel plane would be little affected by till deposition from dead ice but that the principal effect would be to assume a position closer to that of the bed. It may therefore have been more relevant in samples examined to measure dip in relation to local topography rather than to the horizontal. There is no guarantee however of any relationship between present surface forms and the surface of the ground moraine at the stage(s) of deposition considered in the fabrics, although such a relationship does seem likely.

In seven cases (out of 24) a preferred down-ice orientation was noted in the parallel peak. Angles of dip in most samples were generally small and preference within the parallel peak often so slight as to cast doubt on the value of direction of dip as an indicator of ice flow direction. Recent literature confirms such doubt. Holmes (1941) explained a pronounced down-ice dip in terms of movement along well-defined shear planes within the ice or in contact with the glacier bed. Wright (1957) accounts for a pronounced up-ice dip in terms of movement along upward-rising shear planes in thinning marginal ice. Donner and West (1957) found a pronounced down-ice dip in their East Anglian tills and Penny and Catt (1967) pointed to the different interpretations which were possible within a single fabric pattern. Dip direction appears therefore to be of little value as an independent directional indicator. Young (1969) expressed such an opinion after macro-fabric studies on tills near Edinburgh. To make maximum use of fabric data more must be known on the mechanics of glacial deposition in the area in question.

<u>THE DEVELOPMENT OF THE TRANSVERSE PEAK</u>

A strong transverse peak is evident in many samples from the Tweed area (again contrasting with Wright's work in Wadena). An average of 35.7% of stones dip transversely with a maximum of 56% and a minimum of 22% in individual samples. Two potential sources for a pronounced transverse peak involve the shape of the particles (Holmes, 1941; Drake 1972) and the period and mode of transport and deposition.

Holmes (1941) showed that well-rounded and elongated stones (of rhombohedroid shape) were especially adapted to rotational movement and tended to lie transversely. He also suggested that rotational movement was mainly in evidence in materials carried above the glacier bed and here transverse fabrics would be best developed. Harrison (1957) and later workers have indicated the importance of this transportational environment in fabric inheritance. Harrison envisaged a process of melt-out which maintained this transverse strength while Holmes had previously suggested that stones rotating on or near the glacier floor might be pushed down into already deposited till by thrust from higher, faster-moving debris and still maintain their transverse orientation.

Glen, Donner and West (1957) point to laboratory experiments by various authors which indicate that stones immersed in a flowing liquid will initially develop a parallel peak. If flow is continued over a long period a transverse peak will develop. Collision of prolate stones in transit was also suggested as a possible source of the transverse fabric. More recently, Boulton (1972), in observations on currently developing tills in Spitzbergen, suggested that the transverse peak was best developed in narrow till bands between ice layers. Here, debris moved with the ice for long periods and collisions were frequent.

Drake (1974) used the Zingg shape system to classify stones and suggested that transverse patterns appeared to be produced neither by extreme rods (which produced a strong parallel peak) nor by highly prolate shapes, but by stones whose shapes were near the common intersection of the four Zingg shape classes. He suggested that such pebbles lacked sufficient elongationto force the 'a' axis into strong parallelism. Unlike more flattened blades and discs they are insufficiently planar to be forced into maintaining the plane of the a/b axes and are therefore more free to roll about their 'a' axis. Many spherical stones also have this freedom but are generally not elongate enough to provide an axis for rotation frequent enough to maintain a transverse fabric.

Protracted flow would appear to be a major factor in the formation of a strong transverse peak in the Tweed drumlin field results. This flow is envisaged as involving bands of debris above the glacier bed in the manner alredy suggested by stone-count patterns (chapters 3,4 and 5). Material would be supplied to these zones by active upward-rising shear planes resulting from the complex topography of the area, particularly the hills of the Silurian strata or the varied topography of the Old Red Sandstone area with its many igneous intrusions. The role of stone collisions in establishing a transverse fabric is impossible to estimate but its potential must be recognised in view of the abundant debris. No measurements of stone shape were made so that no conclusions can be drawn regarding the impact of this on the fabric. While the shape of some Silurian fragments and many basalts might be conducive to transverse rotational movements, the strengths of many fabrics require other controls to be operating also.

The retention of the transverse strength from the transportational phase through deposition, is significant. While Holmes (1941) envisaged this as being possible during a plastering on process much recent literature suggests that such a process would produce a stronger parallel peak. The melt-out theories of Harrison (1957) seem applicable. The low angles of dip support such a possibility in this case and while no other evidence of melt-out was noted in the immediate sample areas, evidence was present at similar (and greater) depths elsewhere (Figs. 15a to 15d). The compaction of the till could likewise be a product of squeeze melt under thick ice although no quantitative tests were carried out to test this hypothesis. Thus, while the fabrics tend to support earlier theories on the ice and its debris load they yield less on the mode of deposition. In the light of this previous evidence the fabrics are interpretated as illustrating essentially en-glacial origins during protracted flow. The low angles of dip suggest a more widespread application of melt-out ideas than envisaged to date.

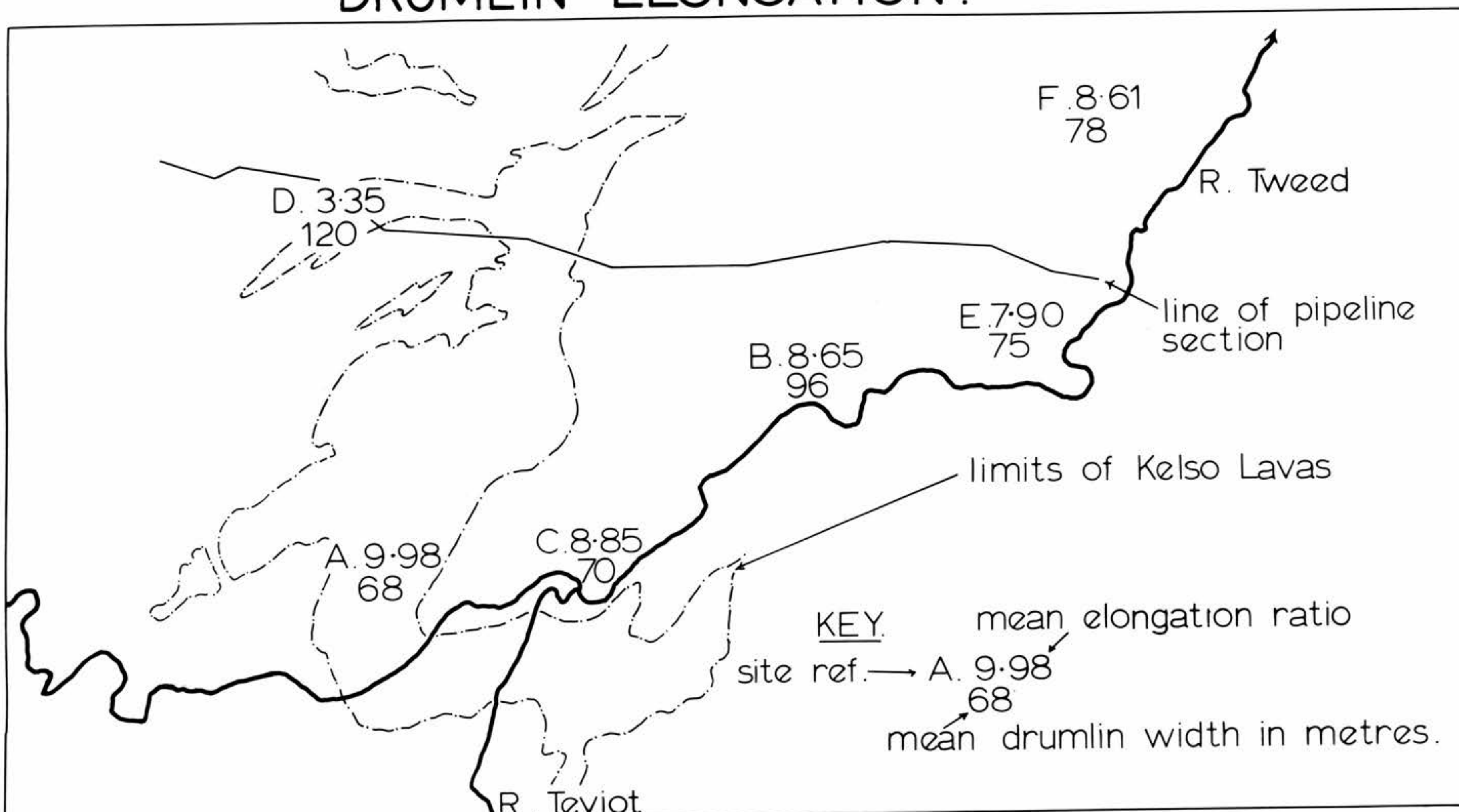
RELATIONSHIPS OF FABRICS TO DRUMLIN FORM

Analyses of till macro-fabrics were made on a number of different drumlins. Studies were carried out in association with the pipeline trench described in chapter 2 and choice of study points on any particular drumlin were limited to this line. In only one instance (orientations 0.14 to 0.19 inclusive) was a closer pattern of analysis possible on the stoss end of one feature (6 sites at 10-12m intervals, similar depth). While it is accepted that studies were carried out on drumlins of different shapes and sizes the results have been related to a single hypothetical drumlinoid form for further analysis. Their approximate relative positions on the constructed drumlin were derived from studies of position relative to their original drumlins.

Variation in drumlin shape is not believed to be random throughout a drumlin field (Hollingworth, 1931; Doornkamp and King, 1971). To test this view in the Tweed area, measurements of drumlin elongation were made on a total of 120 drumlins at 6 sites. Rose and Letzer (1975) have discussed unreliability of drumlin measurement direct from 1:25,000 topographic maps but in the current study the drumlins were first mapped at this scale in the field (J.B. Sissons, unpubl.) and subsequent measurements taken from these detailed field maps. In the assessment of drumlin form in mathematical terms Doornkamp and King (1971) recognise the close approximation between the simple elongation ratio and the mathematically more cumbersome k (constant) in the formula for the lemniscate loop, ($k = \frac{\pi a^2}{4A}$ where A = area and a = drumlin length), and suggest that it is possible to use elongation to assess regional differences in drumlin shape as this measure is more readily obtained. Large k values are seen as being associated with maximum ice pressure, i.e. faster flow. Constant flow will also tend to produce a longer drumlin while changing flow patterns will produce shorter, more rounded forms.

The results of the 6 studies are tabulated at the end of this chapter while mean elongation at each site is shown on Fig. 54a. Elongation appears at a maximum in the centre of the basin in the sites examined around Charterhouse farm (~~M.R.~~ NT 670345) and near Kelso (NT 730340). These produce average values of 9.98 and 8.85 respectively. Previous stone-count analyses (chapters 1 and 6) had already suggested more concentrated ice-streaming towards the centre of the basin as represented in the 'tongue' of Silurian erratics described in chapter six. This may be compared with Hollingworth's (1931) study which also suggested a relationship between faster-moving glacier ice and greater elongation of drumlins. Eastwards down the basin. the degree of elongation decreases only slightly. The sample taken in the area of Swinton village (~~M.R.~~ NT 835475) is slightly anomalous however. This sample shows very considerable range in elongation values - from 2.24 to 32.75. The first ten drumlins measured gave a mean of only 5.5, and omitting the one excessively elongated feature from the total, the mean elongation of the remaining 19 is reduced to 7.3. This sample suggests considerable local variations in elongation both of small groups of drumlins and of individual features. Much more striking however, were the measurements made in the area to the south of Gordon village (~~M.R.~~ NT 645432) where average elongation reached only 3.5 and where standard deviation within this most consistent sample reached only 1.1. The average width of the drumlins was notably greater than that of the other samples and was about 60% greater than that of the Charterhouse site. Less rapid ice flow and perhaps greater variation of flow direction over this higher marginal area are suggested as major influences at this site.

FIG. 54a. REGIONAL VARIATIONS IN DRUMLIN ELONGATION.



The significance of the difference between these 6 areas may be tested by using the analysis of variance test. Results appear thus:

Source of Variance (a)	Sum of squares (b)	Degrees of Freedom (c)	Variance Estimate
between sample	528.03	5	105.60
within sample	2286.85	114	20.06

$$\text{Snedecors 'F' value} = \frac{\text{Greater Variance Estimate}}{\text{Lesser Variance Estimate}} = \underline{5.26}$$

The tabled value of F, 5,114 at the 99% level of significance is about 3.00 so that the null hypothesis of no significant difference between the areas can be rejected and differences between elongation values may be taken to indicate significant differences in drumlin morphology in these 6 parts of the Tweed drumlin field. Results are even more strikingly significant when comparing only site A and site D (the Charterhouse and Gordon sites respectively) and the omission of site F with its great range of values greatly increases the significance of differences among the other 5 sites.

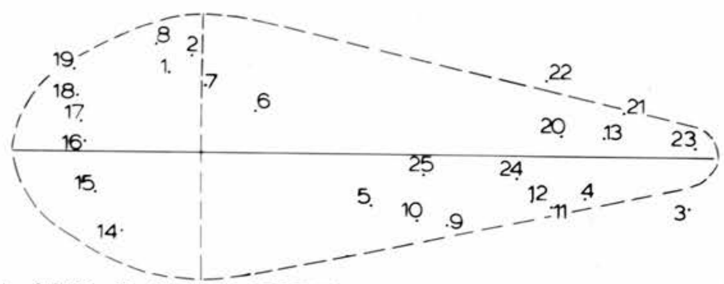
Despite these regional variations in drumlin elongation within the Tweed basin, the individual macro-fabric analyses may still be related to a single hypothetical drumlin in an attempt to analyse their collective significance relative to the drumlin form. Fig. 55 illustrates sample locations on a hypothetical drumlin.

Apart from the problem of transposing orientations from differently shaped drumlins onto a common form, there is the additional consideration that orientations 23, 24 and 25 and potentially 22 lie on the tail of rock-controlled bodies. Studies 24 and 25 for example, lie on the tail of the imposing crag of Knock Hill. Whilst it is possible that the

FIGS. 55, 56a, 56b & 56c.

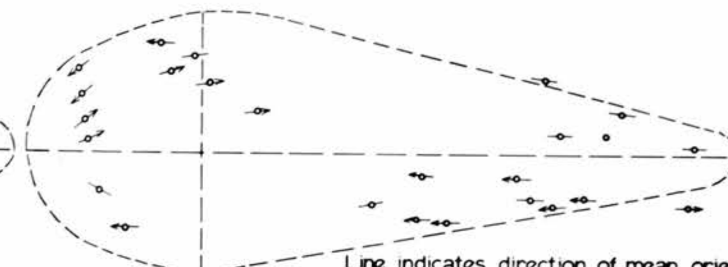
RESULTS OF MACRO-FABRIC ANALYSES RELATED TO A HYPOTHETICAL DRUMLINOID FORM.

FIG. 55 LOCATION OF SAMPLES ON DRUMLIN.



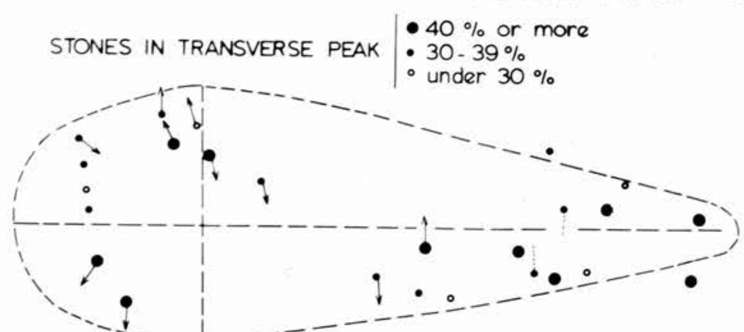
ALL SITES AT SIMILAR DEPTHS - 2m - 2·5m.

FIG. 56a MEAN ORIENTATION & DOMINANT DIP DIRECTION IN PARALLEL PEAK



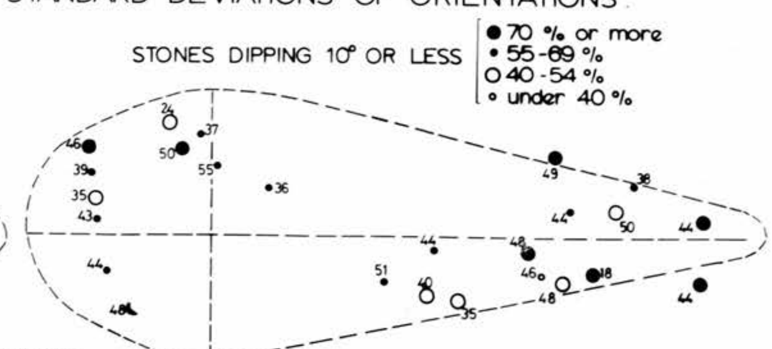
Line indicates direction of mean orientation.
Arrows show dominant dip direction in parallel peak, where this is applicable.

FIG. 56b STRENGTH OF TRANSVERSE PEAK.
DIP TENDENCIES IN THE TRANSVERSE PEAK.



ARROWS SHOW DOMINANT DIP 'N TRANSVERSE PEAK WHERE APPLICABLE

FIG. 56c ANGLES OF PLUNGE OF STONES.
STANDARD DEVIATIONS OF ORIENTATIONS.



99 : FIGURES GIVE STANDARD DEVIATIONS

peculiar conditions of flow around these rock-controlled stoss ends may alter the character of deposition on the lee side there is no immediate evidence of this process having taken place.

Orientations 3 and 22, and to a lesser extent 9 and 10, were difficult to locate on the hypothetical drumlin since they were themselves located on very low streamlined features rather than on any of the larger drumlins Sites 5 and 13 have also been included on the figures although these fabrics are ill -defined, suggestive of modification at some stage.

Fig. 56a shows mean orientation related to drumlin form and also the dominant dip direction within the parallel peak (where applicable). This was measured over an 80 degree arc. (Fabric details are shown on Fig. 49.) Mean orientations show a close relationship to drumlin form, particularly in the curved flow patterns suggested in stoss-end samples but also in the general parallelism of fabrics from the tail of the drumlins. The bulk of stoss-end samples (C.14 to C.19 inclusive) relate to a particular drumlin situated in the area of Hardacres farm, west-northwest of Eccles Village (~~M.R.~~ NT 742418), a long, fairly narrow drumlin with a steep stoss-end.

Many of the tail samples show a preference for an up-glacier dip in this parallel peak, (most exceptions generally exhibiting no peak at all). Stoss-end patterns suggest a dominant up-glacier dip at lower levels on the drumlins, particularly on the flanks. Samples in the centre of the stoss-end and towards the crest appear to dip in a predominantly down-ice direction, <u>i.e.</u> into the drumlin.

Fig. 56b indicates dip tendencies in stones of transverse orientations (100 degree arcs). Percentages of stones in the transverse direction are also shown. Many sites, particularly on tail locations, do not exhibit any dip preference within the transverse peak, but more samples towards the stoss end do appear to do so. Five out of ten samples show a preferred dip out of the drumlin in their transverse peak. These samples are located towards the flanks of the stoss end, while samples showing no preferred dip in the transverse peak or dipping slightly into the drumlin are found in central positions on the stoss end or at higher levels.

Fig. 56c gives an indication of the degree of dip noted in samples. Percentages dipping at 10 degrees or less are shown for each site and the standard deviation of the orientations in each sample is also illustrated. (The relationship between this figure and the development of the transverse peak has already been suggested in this chapter.) No particular pattern emerges in Fig. 56c. Calculations show considerable general similarity between stoss and lee sites in terms of average dip of stones. Taking the numbers of stones dipping at 10 degrees or less in each sample gives an average stoss-end value of 62.4% per sample and average tail values of 61.2%. (Overall mean = 61.7.) Stones dipping at 40 degrees or more give identical mean values of 5.1% per sample, in both stoss and tail samples.

RESULTS AND LITERATURE

Although the term 'drumlin' is in widespread use there appears to be some lack of precision in its application; in particular a great range of elongation has been noted in features described as drumlins. At one extreme are the "long, linear drumlins" studied by Lemke (1958) near Velva in North Dakota. These steep-sided, sharp-crested features achieved a maximum elongation of 240:1 in one long feature, several kilometres in length. Similar elongation has been observed on much smaller features throughout the de-glaciated areas of North America. Dyson (1952) examined features of 150-180 m in length, 0.6-3.7 m wide and less than one metre in height in from of the Grinnel and Sperry glaciers. Many features of such elongation probably fall within Boulton's (1976) suggested genetic classification of flutings. Embleton and King (1975) on the other hand, suggest 'normal' drumlin elongation to be of the order of 2.5:1 extending to 3 or 4:1.

Variations are apparent even within single drumlin fields. Hollingworth (1931), working on the drumlins of the Eden Valley and Solway lowlands, measured the elongations of 20 drumlins at each of five sites. Individual elongations varied from 1.1:1 to 9.7:1 with a mean of 3:1. Although a range was noted within each group of 20, statistical tests suggested that variation between groups was greater than that within groups and thus change in elongation over the drumlin field was indicated. Kupsch (1955) working in a low density drumlin field in Saskatchewan measured elongations around a mean of 2.5:1. Length varied between 75 and 750 m with widths of 25-30 m in the more elongate examples. Wright's (1957) drumlins, in the tills west of Lake Superior, range from elongate forms (12 km x 0.5 km) to oval (0.7 km x 0.5 km) while height varies generally from 5-10 metres. The Tweed drumlins have already been shown to exhibit regional changes in elongation in a manner similar to that presented by Hollingworth.

Drumlin form has also been examined from a mathematical standpoint Reed <u>et al</u>. (1962) found that the shape of the drumlin base approximated to an elliptical form. Their studies of orientations and spacings yielded evidence of preferred spacings (despite a wide variety). Chorley (1959) compared the drumlin to other streamlined forms, e.g. aeroplane wings, and indicated that the form was not symmetrical about two axes as an ellipse but may only be symmetrical about the longitudinal axis. As drumlin size increases so does asymmetry about the long axis. Carrying the analogy with aeroplane wings farther, Chorley suggests that greater elongation of the drumlin may be associated with faster ice flow a view apparently supported by evidence from the Solway and Tweed areas.

Doornkamp and King (1971) in their consideration of the mathematical aspects of drumlin shape support this view that large 'k' values (which approximate to the elongation ratio) are associated with maximum ice pressure and thus potentially faster flow.

Drumlin composition, like drumlin shape, appears equally varied in the literature. Varying amounts of stratified materials have been described in features identified as drumlins. Lemke's supposed drumlins were apparently built around cores of stratified sand, for example, while Kupsch noted "walls of jointed boulders in his drumlins, apparently providing nuclei around which drumlins were constructed. In the Tweed area basalt boulders appeared often to be in clusters and on one occasion this was towards the stoss end of a drumlin, although it is not suggested that these provided nuclei for drumlin formation. Rather the explanation may lie in the varying local conditions of deposition (Boulton, 1975) or in the collision or retarding of these large clasts at a late stage in the total build up of the drumlin form as envisaged by Boulton (1975).

The idea of some form of obstruction being necessary for drumlin formation has been examined by other authors, (e.g. Gravenor, 1953). The potential connection between drumlin and crag and tail is thus established and in the Tweed drumlin field the frequency of the latter in the up-glacier areas has already been indicated. In drumlin formation itself it need not necessarily be rock cores that initiate drumlins; lumps or mounds of frozen till, brought about perhaps by some degree of periodicity in ice-flow patterns or deformation of sub-glacial drift might be equally effective but not detectable today. The mechanics of till deposition in general are not yet fully understood however and it is only recently that an attempt at a detailed theoretical approach has been evident (Boulton, 1975). The relevance of these recent theories will be discussed in relation to deposition in general in the concluding chapter.

The possible role of the crag-controlled bodies in initiating further drumlin formation or in effecting drumlin spacing down-ice is difficult to evaluate, although Boulton (1975) points to streams of debris-rich ice being created by streaming of debris-laden basal ice around major obstructions in the glacier bed. The activity in the basal ice initiated by movement over the excessively moulded, rock-controlled topography of the Silurian and, more particularly, the Old Red Sandstone areas, might be a critical factor in drumlin formation down-glacier however, particularly if associated with some degree of periodicity in debris-rich ice.

Till fabric studies in drumlin areas have been limited. Wright's (1957) study did not attempt to evaluate results in terms of their relevance to drumlin form in detail. Stone-orientations were claimed to be parallel to drumlin direction in a general sense. Till fabric studies in a drumlinoid feature in Wensleydale, Yorkshire (Andrews and King, 1968) showed preferred orientations often at considerable angles to drumlin alignment. Deviations from the direction of the long axis of the drumlin varied from 12° to 54° with a mean of 33° in 10 samples of 50 stones each. Eight out of ten samples showed a statistically preferred up-glacier dip. This does not equate with results from the Tweed area (Fig. 50). Orientations in the Yorkshire site pointed in towards the centre of the drumlin and from the base upwards there was a gradual increase in divergence between drumlin alignment and mean vector orientation with samples nearer the summit showing less consistency within themselves. This evidence was interpretated as suggesting that the glacier ice was pressing material against the sides of the drumlin with an element of lateral stress, (which was missing near the summit of the drumlin). Wright (1957) also pointed to lateral movement associated with laterally spreading ice in the Wadena area while Kupsch, in his analysis of boulder fracture systems postulated ice re-advance over frozen moraine with pressure from top and bottom of the drumlin being relieved by lateral movement.

The Tweed results do not appear to re-enforce the pattern suggested by Andrews and King, particularly since they lack the alignment towards the centre of the drumlin. A dominant up-glacier dip was noted in the Tweed fabrics however, although the exceptions to this rule appeared to be concentrated towards the centre and crest of the stoss end. The significance of this is not readily apparent. Boulton (1975) in considering the flow of basal ice around an obstruction in the glacier bed "identified" thickened streams of debris-rich ice in the troughs around the flanks of the obstruction with thinning of the debris layer over the summits. Flow lines along the crest descended towards the bed on the stoss end and this may have some influence in the creation of a down-ice dip during lodgement with clasts being pushed into the drumlin by those descending flow lines. In terms of angles of dip the stoss end sites in the Tweed area were essentially similar to tail sites

In making comparison with the Yorkshire site of Andrews and King (1968) however, conclusions are limited in that the Tweed results relate to a common depth and to a variety of locations on several drumlins whereas the Wensleydale fabrics relate to a single section on a suggested drumlin with samples from a variety of depths.

The Tweed samples appear to produce patterns similar to those encountered by Gravenor (1974) in the Yarmouth drumlin field in Nova Scotia. Gravenor found well-defined fabrics at depths of 2-3 m (i.e. at similar depths to the Tweed samples). Fabrics examined by Gravenor at depths of 6-8 m produced poorly defined fabrics. (There are no equivalent fabrics in the author's Tweed results.) Gravenor also presents evidence for a divergent pattern of flow around the stoss end, with deviations of up to 50° from the line of drumlin orientation. Maximum deviations in the author's studies reach 70° in the steep stoss end of the Hardacres drumlin. Mean 'k' values in Gravenor's study were in the order of 2-3, i.e. generally lower than those of the more elongate features characteristic of the Tweed area, although the pattern in Gravenor's case is influenced by an apparent re-advance of ice over the drumlins in a direction almost opposite to that involved in their original formation.

The Tweed results suggest a very clear pattern of streamline flow around the drumlin form. Till fabrics examined here have already been suggested as being deposited from debris-rich ice which may or may not have been active in all cases. The fabric patterns as a whole clearly suggest evolution under active ice but this need not necessarily indicate actual deposition from moving ice in all cases. The dip outwards from the drumlin flanks noted in some transverse orientations for example (Fig. 56b), could possibly result from some adjustment of debris in the parallel plane during deposition, i.e. reflecting the slope of the drumlin at that point rather than any englacial activities.

It is suggested that these results cannot be interpretated to yield new information on the actual formation of a drumlin. Rather fabrics at these levels must represent the movement of the glacier as it flowed around the already initiated drumlin form, building around this pre-existing structure perhaps by plastering-on from slow-moving, debris-rich ice or possibly by melt-out in many instances. The fabric patterns themselves are mainly interpreted as the products of en-glacial activity, both in the development of an overall up-ice dip and more particularly in the marked growth of the transverse peak.

RESULTS OF DRUMLIN ELONGATION STUDIES

E/R : Elongation Ratio

a : drumlin length (metres) *w : drumlin width (metres) *Superimposition of drumlins is common in parts of the Tweed basin and drumlin width was measured at the widest point where a single drumlin could be recognised.

SITE A CHARTERHOUSE FARM (M.R. NT 670346)

a	w	E/R	a	w	E/R
500 metres	88 metres	5.71	830 metres	45 metres	18.44
355	30	11.83	725	108	6.74
700	48	14.73	625	58	10.87
280	33	8.54	365	75	4.87
855	75	11.40	513	95	5.39
930	75	12.40	1681	75	22.40
500	73	6.90	728	53	13.85
555	58	9.65	875	88	10.00
585	75	7.80	355	43	8.35
363	90	4.03	393	70	5.61

Standard deviation of E/R values = 4.6

SITE B ECCLES HOUSE (M.R. NT 763412)

a	w	E/R	a	w	E/R
855 metres	103 metres	8.34	653 metres	73 metres	9.00
1320	180	7.33	625	173	3.62
385	83	4.67	950	98	9.74
585	68	8.67	1700	135	12.60
175	45	3.89	823	98	8.44
1305	70	18.64	810	93	8.76
1553	133	11.72	683	95	7.18
480	75	6.42	555	135	4.11
695	45	15.44	495	70	7.07
425	70	6.07	1225	108	11.40

Standard deviation of E/R values = 3.76

SITE C — BETWEEN EDNAM VILLAGE and FLOORS CASTLE IN THE AREA NORTH OF KELSO (M.~~R~~. NT 725345).

a	w	E/R	a	w	E/R
280 metres	70 metres	4.00	250 metres	73 metres	3.45
400	68	5.92	375	53	7.14
1028	70	14.68	475	58	8.26
1495	778	1.92	405	45	9.00
1063	53	20.24	330	48	6.95
1200	68	17.78	355	50	7.10
455	48	9.58	900	65	13.85
405	70	5.79	600	35	17.14
400	50	8.00	625	180	3.47
800	120	6.67	450	75	6.00

Standard deviation of E/R values = 5.04

SITE D — EAST AND SOUTH OF GORDON VILLAGE (M.~~R~~. NT 646431)

a	w	E/R	a	w	E/R
378 metres	195 metres	1.94	255 metres	40 metres	6.38
225	115	1.95	330	120	2.75
525	123	4.29	525	205	2.56
153	95	1.61	428	125	3.42
400	103	3.90	485	143	3.40
425	173	2.46	328	78	4.23
496	125	3.96	433	58	4.02
343	105	3.26	240	55	4.36
450	100	4.70	555	173	3.22
283	128	2.22	358	150	2.38

Standard deviation of E/R values = 1.14

SITE E — BETWEEN HIRSEL (NT 830407) AND LENNELHILL FARM NT (860429)

a	w	E/R	a	w	E/R
725 metres	250 metres	2.90	750 metres	63 metres	12.00
425	53	8.10	675	50	13.50
253	45	5.61	400	43	9.41
975	85	11.47	438	45	9.72
363	70	5.18	800	135	5.93
375	128	2.94	613	100	6.13
460	55	8.36	900	113	8.00
1000	78	12.90	1775	118	15.10
353	75	4.70	1128	105	10.60
650	78	8.39	475	68	7.04

Standard deviation of E/R values = 3.39

SITE F SWINTON HOUSE (M.R. NT 818472)

838 metres	103 metres	8.17	550 metres	58 metres	9.57
830	95	8.74	375	70	5.36
770	95	8.11	550	55	10.00
1005	73	13.86	263	48	5.53
938	80	11.72	325	80	4.06
635	50	12.70	280	123	2.29
545	83	6.61	253	113	2.24
1638	50	32.75	325	125	2.60
550	75	7.33	425	53	8.10
375	55	6.82	475	83	5.76

Standard deviation of E/R values = 6.4 (Omitting the one excessive value, S.D. = 3.5)

CHAPTER NINE

A STUDY OF ERRATICS FROM THE BLACK HILL TRACHYTE MASS

Introduction

The purpose of this study was to examine in detail the spread and concentration of one clear indicator stone in relation to local ice movement and topography.

Sampling was concentrated near the ground surface, only some 30-40 cm of material being removed. 100 stones were examined at each site. In choosing surface sampling, the controls were partly in that it was considered preferable to take a large number of surface samples (despite possibilities of error due to selective weathering or man's influences), than to take a small number of samples at depth. Human interference however is potentially minimal over much of the area in that large tracts are under permanent pasture or woodland. Surface sampling also implies that results must be associated most closely with the last ice direction as represented by ice-moulded forms. Since results to date had suggested very active ice in this area it was hoped that a localised study of erratics movement might contribute to this point.

This study was localised for two main reasons; firstly the aim was to study local trends in detail, thus necessitating a high sample density and secondly because of geological controls. As the study progressed it became clear that the lateral spread of erratics down-glacier was considerable and contamination of stone counts by stones from other trachyte bodies became more and more likely. The identification of Black Hill trachyte as distinct from that of White Hill or the Eildon

Hills is often difficult in the hand specimen and thus the danger of contamination is very real,

The geology of the site is shown in Fig. 57. The Black Hill outcrop rises steeply some 90m and more above the Leader valley to a sharp summit that slopes gently north-eastwards. Rock is exposed at about 243m on the southern side and just above this level on the north. At about 153m on the west side is a small lenticular outcrop. The rock is identified as porphyritic quartz-riebeckite-trachyte (Geol. Surv., unpubl.) and the whole mass is suggestive of a sill-like intrusion. Stretching east-northeast from the summit is a long tail of c.3 km length, steepest on its southern side, especially nearer the crag, and becoming much less distinct down-ice on the northern flank.

Rising over 210m some 1000m approx. to the north-west of Black Hill and separated from it by a depression at c. 150m O.D. is the lower flatter bulk of White Hill, a similar acidic intrusion. South-east of Black Hill some 1200m away across a marked depression is Redpath Hill, part of a small group of basaltic hills rising to around 240m. Long tails run off east-northeastwards from these basalt exposures, referred to previously as the Brotherstone Hill Group. Between Black Hill and Redpath Hill, slightly down-ice of the gap, the land rises towards a flattish ridge of just over 150m. Off the southern flank of this ridge rises a larger drumlin, apparently with a trachyte core (Geol. Surv., unpubl.). This land is cultivated and stone-counts and soil colouring suggest Old Red Sandstone bedrock to be at little more than 1m below the ground surface, on the flatter part particularly. Trachyte counts increase locally to indicate the buried core. Down-ice of this ridge and of the tails of the Brotherstone Hill Group, drumlinoid forms became apparent.

PREVIOUS STUDIES

In the past hundred years many studies of glacial dispersal have

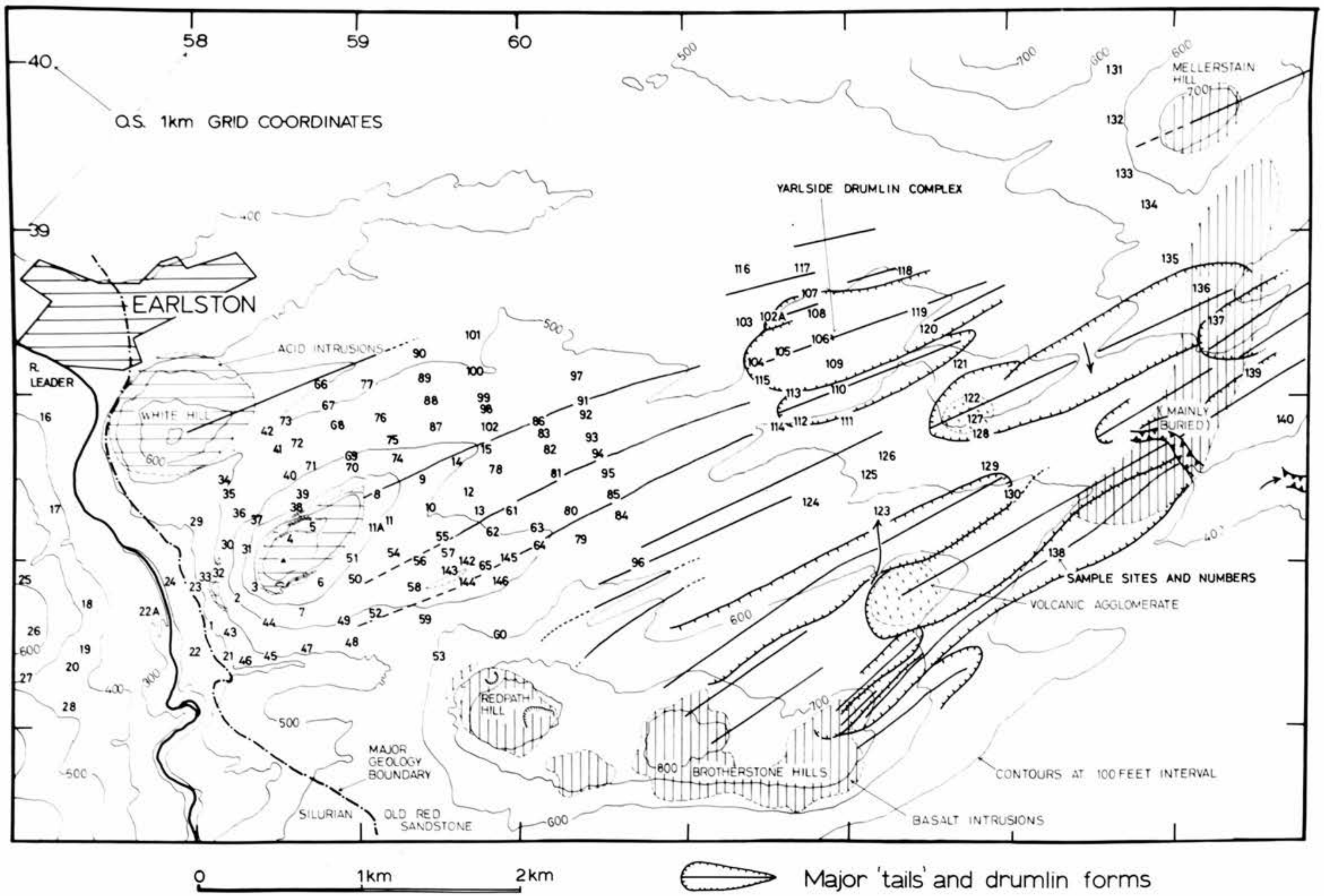


FIG. 57 BLACK HILL STUDY: RELIEF, GEOLOGY, SAMPLING SITES.

been made and a considerable literature exists. Initially most indicator studies involved boulder or pebble-size fragments and many of the igneous rocks of Scotland have provided the subjects of significant erratics studies. A classic early study was that of A.M. Peach (1909) on the essexite of the Lennotown boulder train. One of the major findings of this work was the concentration of the essexite within a relatively narrow band down-glacier of the outcrop, this band measuring only about 6 km across at a distance of 56 km from the outcrop for example.

It is the granite rocks of Scotland in particular however that have been used by many workers in the plotting of regional patterns of ice movement, e.g. the various granites of South-west Scotland (Charlesworth 1926a); the granites of Glen Fyne (Hopkins, 1852), Etive (Kynaston et al., 1968) and Rannoch (Hinxman et al., 1923) etc.. The work of Hinxman et al. (1923) on the movement of the Rannoch granite also yielded spectacular examples of the uphill carriage of large erratics for as much as 600m.

In the last twenty years, particularly in North America, many studies have involved the use of sand-size minerals, clay minerals and various trace elements. Many of these techniques have been commonly applied in conjunction with other indicators in the assessment of regional ice movement or in till differentiation. Beaumont (1971) for example successfully used stone-count techniques in association with orientation analyses in his work on the tills of East Durham.

Many recent workers have begun to analyse more closely the relationship between erratics, their concentration in tills and the local bedrock in the manner attempted earlier in this thesis, (e.g. Dreimanis and Vagners, 1969, 1971; Shilts, 1973; Gillberg, 1968 etc.). Dreimanis and Vagners (1971) recognised that local rocks were not always predominant in tills and discussed the role of comminution in the englacial environment.

They suggested at least a bi-modal frequency polygon for any rock type within a till, further peaks being dependant on processes other than crushing which might be in operation. The main peaks envisaged by Dreimanis and Vagners were initial concentration in the coarser fraction with the first inclusion of rock in the till and a second peak in the terminal grades of the constituent minerals after prolonged transport. Gillberg (1967) indicated how the gradient of such a line might be further controlled by rock type and the differential susceptibility of different rocks to abrasion during transport.

Englacial and subglacial conditions and activities during deposition are obviously difficult to examine and assess but other variables can be studied. Gillberg (1965, 1967) and Shilts (1973), for example, have noted the role of even relatively small topographic prominences in acting as obstacles to erratic movement, Gillberg recognising principal erratics routes along the valleys with obstructions on the higher plateau areas. Shilts (1973), in more gently rolling topography, also examined the overall pattern of distribution and found that, whereas the maximum limits of distribution were fan-shaped in plan, he could recognise major concentrations of most components along parallel or sub-parallel bands.

THE RESULTS

The results of the Black Hill study are illustrated in Figs. 58 to 61. Percentage concentrations are given for each erratic type at each site. In addition ispleths have been drawn in by interpolation, the 10%, 20% and 30% isopleths being shown by the thinner lines and the 50%, 70% and 90% isopleths by thicker lines.

Attempts were made to produce computerised trend surfaces for the trachyte and basalt data but the data proved unsuitable. On the scales used, the trend surface was unable to fit to the sharp peaks of percentages and tended to smooth these out, consequently producing a poor fit with high positive residuals at the peaks and high negative ones away from them. On the trachyte percentage 'F' tests confirmed that percentage explanations were so low as to have potentially arisen by chance using random data values (D.J. Unwin, 1970). Although percentage explanation for basalts produced better results and 'F' test indicated a second order surface to be best, the validity of the result was in doubt since the surface is unable to fit to the large number of zero values since there are no negative percentages to balance up the positive ones. Consequently such trend surfaces would be of little use in the further interpretation of the results of this study. Examples of surfaces are given in Fig. 57a.

The Tracyte erratics Plots of the trachyte erratics are shown in Fig. 58. The general pattern illustrates a strong band of volcanic debris along and parallel to the tail of Black Hill but shows interesting variations within this. In the first 2 km of the tail for example on both north and south sides, concentrations of trachyte erratics are greatest on either side of the tail rather than on the crest. On the south side there are several markedly high counts towards the base of the pronounced depression running alongside the tail. (Recent slopewash/ alluvial deposits made counts in the absolute base of the depression impossible.) This appears to suggest that the most powerful erosive action came from ice being forced around the flanks of the crag and indeed the major rock exposures today are located on these flank areas. Counts are consistently over 50% at over 1 km from the summit of Black Hill, reaching over 90% in very shallow tills on the summit area.

The suggested trachyte core in the large drumlinoid ridge south-east of Black Hill (G.R. NT 595369) is reflected in an increased trachyte count on some down-glacier parts of the feature. The effect appears fairly localised however, falling off markedly in the deeper tills towards

FIG. 57a. TWO EXAMPLES OF TREND SURFACE ANALYSES ASSOCIATED WITH ERRATICS STUDIES AROUND BLACK HILL.

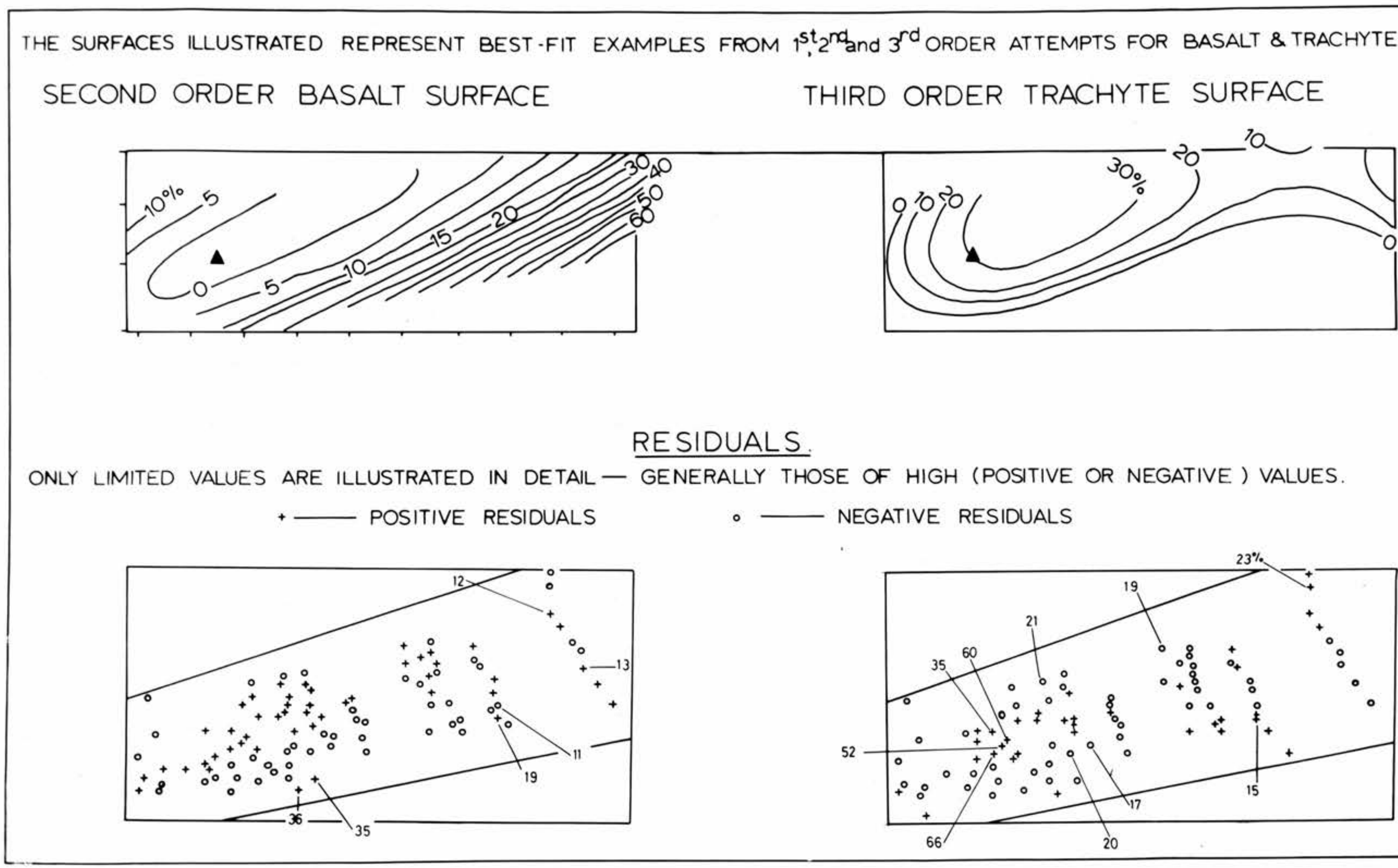
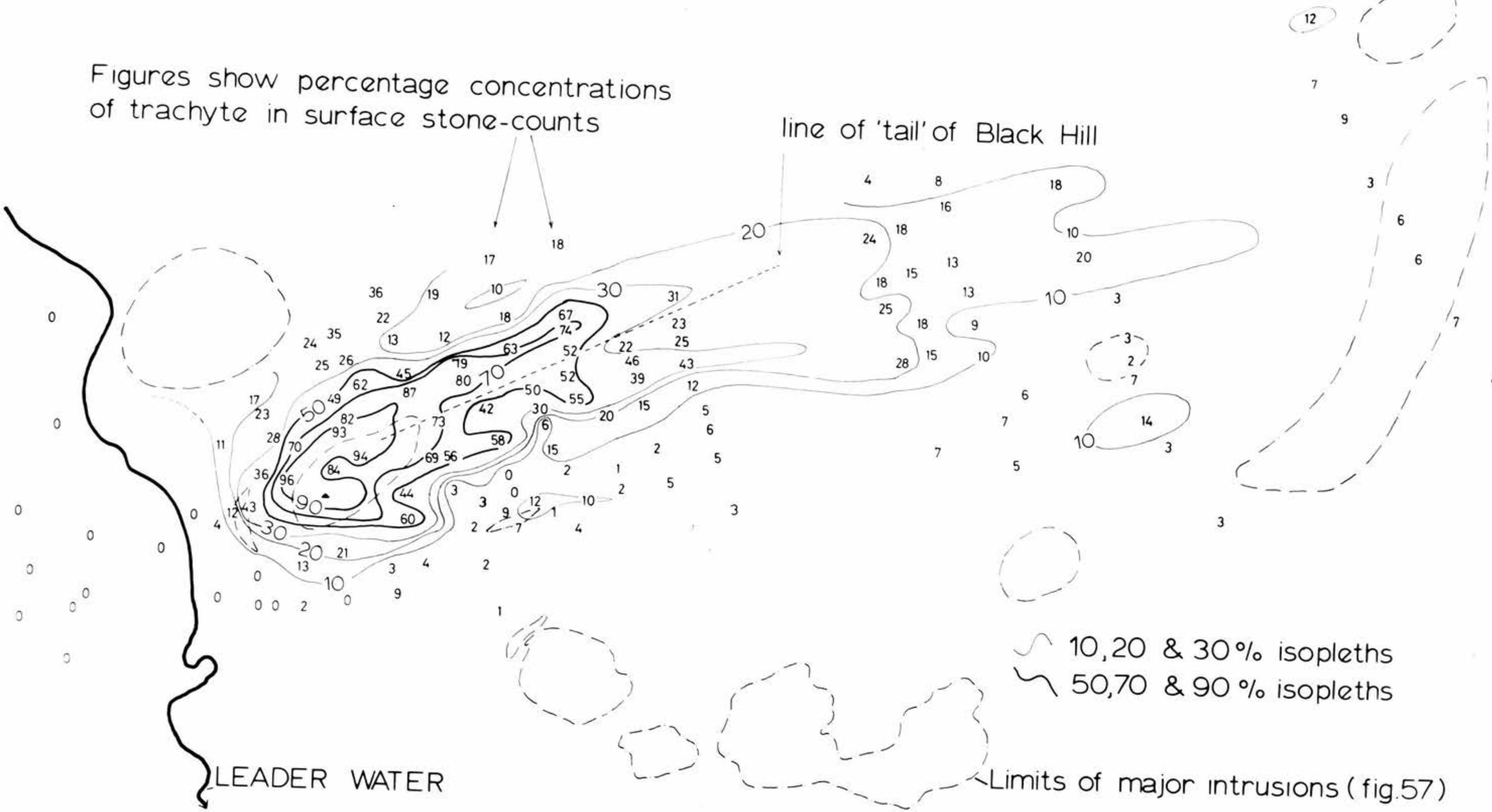


FIG. 58. Black Hill Study: TRACHYTE ERRATICS.



the lower tail area and onto neighbouring features.

There is also evidence of quite marked movement of materials at varying angles across the line of ice movement (as indicated by streamlined forms). On the southern flank areas concentrations of 9% trachyte are found at an angle of 40 degrees to the nearest potential source areas, while on the northern flank an 11% concentration lies at 80 degrees to the direction of ice movement, down glacier of its likely source area. In both cases however, though more particularly the latter, there exists the possibility of downslope movement of materials in the late stages of deglaciation. No evidence was found to support such an occurrence however. Other examples of up to 5% trachyte concentrations are found at angles of 30 degrees and more down-glacier on the southern flank but this time in elevated positions adjoining streamlined forms and therefore inexplicable in terms of possible downslope movement. The evidence thus indicates appreciable lateral movement of materials within the ice and thus fairly active shearing and debris movement in the basal ice. It may be possible that this basal ice moved much more closely in response to local topographic variations than ice at higher levels yet it still appears that some materials were able to move markedly through the ice at some variance to the general direction of glacier flow.

A fan shaped distribution of erratics spread over 90 degrees is therefore suggested in the immediate lee of the Black Hill outcrop. Farther down-glacier the topographic control of the very large basalt intrusions and the contamination by other trachyte sources make limits more difficult to determine. Despite this considerable spread, there occurs a marked concentration in a main erratic stream in a narrower band closer to the pronounced tail feature. By some 6km down-ice however this main concentration has become apparently less marked and in a belt some 3km wide all counts but one (12%) have fallen to under 10%. The southern limit of this belt is characterised particularly by the rise of basalt concentrations from the Redpath and Brotherstone hill groups. In this area too there exists the likliehood of contamination from the trachytes of Eildon and Bemersyde although such a possibility may be at the least slightly diminished by some possible blocking effect from the basaltic hill group. Towards the north contamination from White hill erratics was undoubtedly present in view of the proximity of the intrusion.

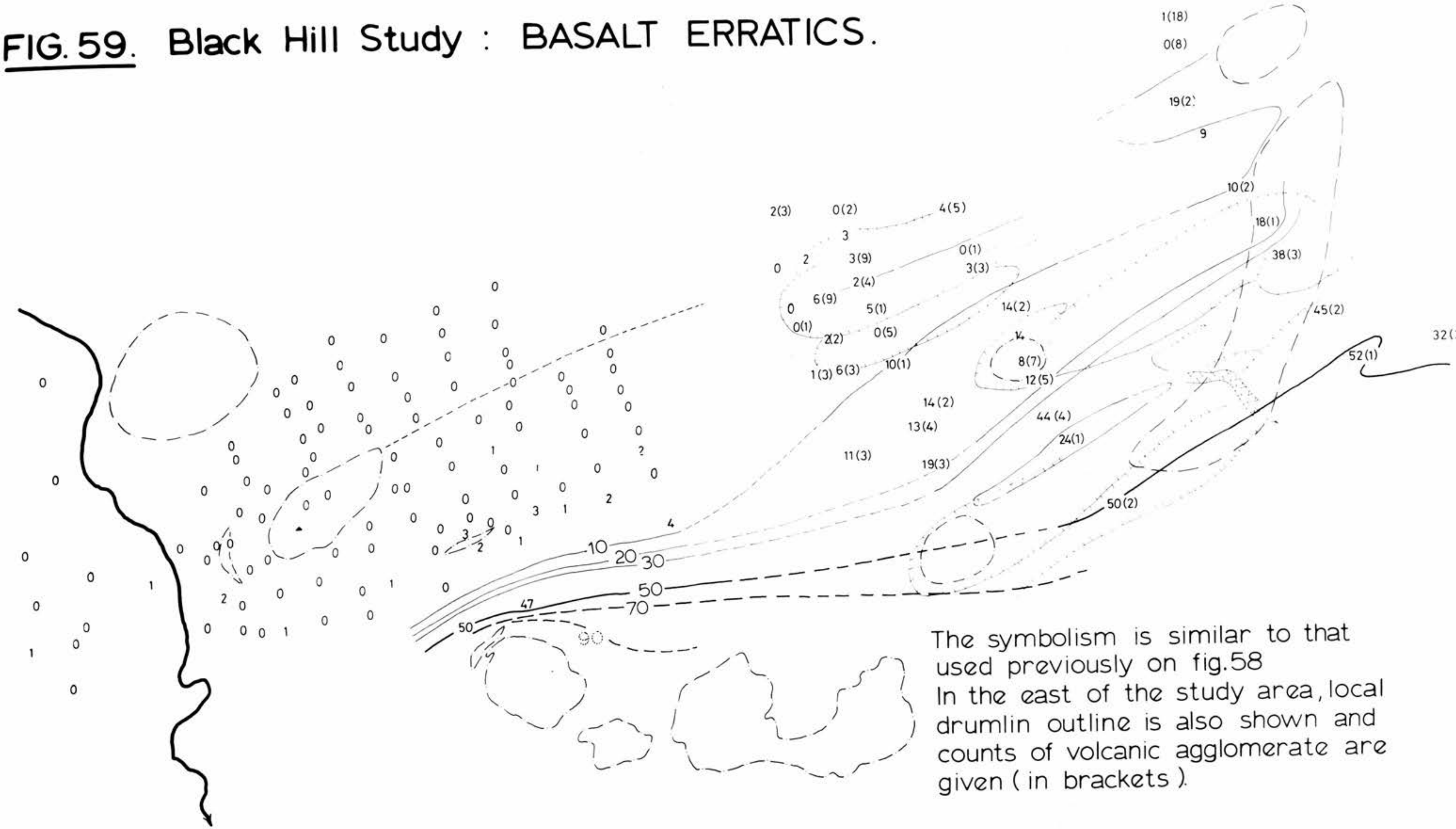
The decline in trachyte concentrations with distance is significant. In quite thin stoney tills on the tail, only a little over 1 km from the outcrop, concentrations had fallen from over 90% to below 50% and then further decreased to below 30% in the next few hundred metres. By 5 to 6 km down-glacier concentrations are generally below 10%. There are several reasons for such a relatively rapid rate of decline.

With increasing distance from source, the trachyte erratics are liable to considerable dilution as they are incorporated into tills dominated by Silurian erratics. The area of the Black Hill exposure is small in comparison with the vast expanse of Silurian strata up-glacier of the study area and the consequent supply of erratics in relative proportions.

The considerable topographic prominence of Black Hill itself is testimony to a certain resistance to erosion of the trachytic body in comparison with the surrounding rocks and thus perhaps to a comparatively lesser supply of erratic material. Conversely however, and possibly as great a contributory factor, the trachytes show considerable susceptibility to fracture and shatter, and it was significant that many of the trachyte erratics encountered were flattish angular fragmentsof small size. It may be that, with the excessive crushing and grinding to which fragments would be subject in active ice, the trachyte erratics would be relatively quickly reduced to the terminal grades of the constituent minerals (Dreimanis and Vagners, 1971). It was notable that no trachytic boulders were encountered other than in the immediate vicinity of the outcrop and most of these were angular fragments suggestive at most, of minimal ice transport and more probably periglacial or post-glacial in origins. While no measurements was made of stone size or weight during stone counts, remarks in field notes consistently refer to smallish angular trachyte fragments, even in close proximity to the outcrop and in the shallow tills overlying parts of it. It seems therefore that any diminution of trachyte percentages is readily explicable, particularly in the degree of dilution in Silurian or Old Red Sandstone dominated tills and in the apparent susceptibility of the erratics to crushing and fracture during transport.

<u>The basalt erratics</u>. Up-glacier of the study area very few basalt outcrops occur, being restricted to a few generally small dyke intrusions. Basalt erratic content in these tills is negligible, being generally below 1%, and most counts in the study area gave zero counts of basalt. Towards the south and east of the Black Hill study area however, basalt counts are markedly increased, almost totally in response to supplies off the Brotherstone and Redpath hills exposures. Towards the eastern margins of the study area (Fig. 57) other basalt bodies begin to contribute, notably the large intrusion near Rachaelfield Farm, (N.G. NT 639378). Samples 137, 139, 140 and 141 (Fig. 57) show a recovery in basalt percentages which have been generally declining down-glacier. This recovery is mainly due to erratics from the large Rachaelfield intrusion which for the most part is buried under drift of at least 1-2 m in thickness,

FIG. 59. Black Hill Study : BASALT ERRATICS.



The symbolism is similar to that used previously on fig.58
In the east of the study area, local drumlin outline is also shown and counts of volcanic agglomerate are given (in brackets).

the thickness of drift explaining the relatively limited rise in basalt counts despite the large size of the intrusion.

The immediate lateral spread of ice off the northern flank of Redpath Hill appears less dramatic than that noted for the trachytes from the flanks of Black Hill (Figs. 58 and 59). Samples 123-126 (Fig. 57), 19, 11, 13, and 14% basalt respectively, are perhaps surprisingly low in view of their position relative to the basalt intrusions and ice movement, and particularly in the light of results of similar areas relative to the trachyte counts. It is possible that ice being deflected by the Black Hill massif would be pressed against this northern flank of Redpath Hill, thus flowing powerfully past. Erratic spread tends to be much more marked about 1½ km down-glacier of the gap between the two hills. At this point there is again apparent evidence for erratic movement across the grain of the landscape at angles of 20 to 25 degrees to the north of prevailing ice movement in this instance. The low values in samples 123-126 are not explicable by any ice deflection however. They were taken in an area of difficult marshy terrain where there was a suspicion of late-glacial or post-glacier deposition by meltwaters or subsequent slopewash. Many of these areas were remarkably low in their stone content.

Complications exist in the assessment of the basalt patterns however, mainly from two sources. Firstly, new basalt sources make additional contributions to the tills, notably the large body in the area of Rachaelfield farm, but also potentially the exposures towards Dryburgh (~~M.R.~~ NT 592322, Fig. 5) and to the south-west of the Eildon Hills. Secondly, it seems likely from stone-count results that other smaller intrusions exist in this area that are not shown on geological maps available to date. This is particularly reflected in counts of volcanic agglomerate and basalt on a drumlin lying immediately down-glacier of the tail of Black Hill and to the south of Yarlside farm (M.R. NT 618387). (Percentage counts of agglomerate are indicated in brackets beside the basalt percentages on Fig. 59.)

Counts of basalt reach a maximum of only 6% on this drumlin, other counts ranging from 0 to 5%, and although this does not represent major concentrations it is a marked change from patterns encountered up-glacier. It may be argued that the basalt counts could result from a lateral spread of erratics from the Redpath and Brotherstone hills, and that percentages and angles of spread are in accordance with results which might be expected in the light of the trachyte counts. The agglomerate concentrations on the other hand (Fig. 59) suggest a much more local source, probably towards the stoss end of this large drumlin. Percentage concentrations of agglomerate in the lee of two other small necks buried in the stoss ends of drumlinoid features in the study area, confirm such a hypothesis. In both of these cases the agglomerate is identified in the stoss end of the feature and the formation of the drumlin is clearly controlled by the igneous body. It is suggested that results from the Yarlside drumlin show that it too has formed around a core of igneous material. It is not possible to ascertain whether the complex nature of the feature (Fig.57), typical of many drumlins in the Tweed area in general, is the result of geological controls also, or of some other factor(s).

Very high agglomerate counts in sample 131 are related to another major neck, that of Fans Hill (M.R. NT 628401).

<u>The Old Red Sandstone erratics.</u> In the light of previous surface counts of Old Red Sandstone erratics (as outlined in Chapter 4) the general pattern of their surface concentration in this Black Hill study shows relatively high counts over much of the area. The Old Red Sandstone erratics show a much more localised system of peaks and troughs in their

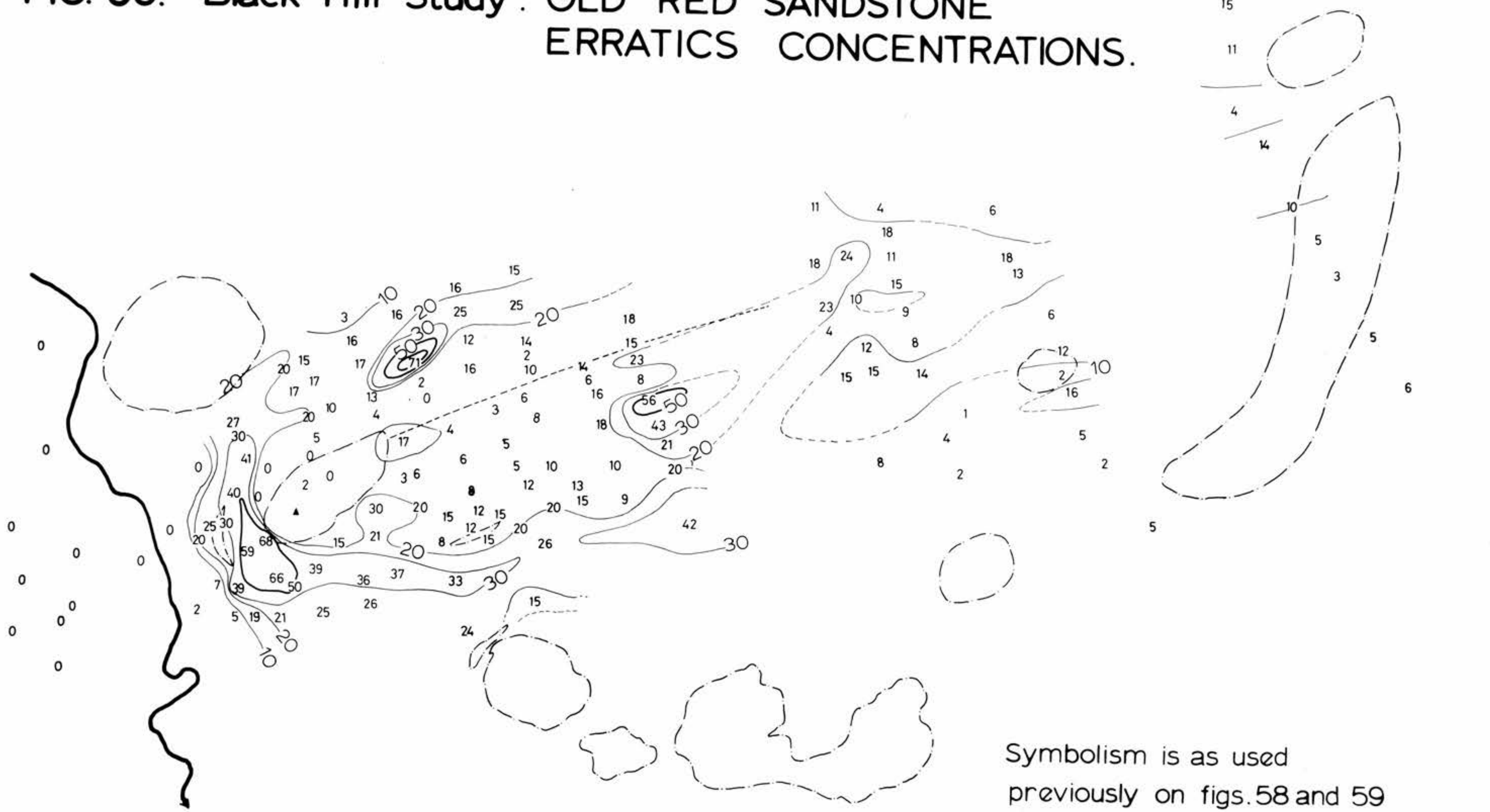
percentage concentrations (Fig. 60) and this must largely be seen as a response to the depth of till locally overlying bedrock. Studies along the pipeline section in the Old Red Sandstone area (Chapter 4) suggested that surface concentrations of Old Red Sandstone of 10% or more were indicative of shallow tills, especially towards the west of the Old Red Sandstone area. As little as one metre below the trench surface (approximately 1.4 m below present ground surface) the till might approach almost total Old Red Sandstone saturation, with solid bedrock less than one metre below this.

Maximum Old Red Sandstone counts in the region of 70% were measured at two sites in the Black Hill study area and these indicate very shallow tills (probably less than one metre deep). The first site lies at c.214 m O.D. on the 'exposed' face of Black Hill where Old Red Sandstone bedrock lies between the upper and lower trachyte exposures (Fig. 57). A maximum count of 68% is recorded here. These high counts do not continue upwards onto the summit area of trachyte bedrock at all, quickly declining to near zero in this area, but counts of 30 to 40% are recorded forming a curving pattern around both flanks of the massif at around 185 to 190 m O.D. indicating clearly the diverging paths of ice at this level, in a manner similar to that suggested in fabric analyses on the Hardacres drumlin (Chapter 8).

The other 70% count of Old Red Sandstone occurs in an isolated peak in sample 76 (Fig. 57). This sample occurs in an area of low local relief, apparently flutings in thick ground moraine. Such a result however suggests very shallow till locally and perhaps a greater degree of bedrock contol than might otherwise have been supposed from surface expressions.

Other high counts of Old Red Sandstone appear in samples 94 and 95 (Fig. 57) located on the flattish moulded ridges lying immediately south of the tail of Black Hill across a pronounced depression. Again

FIG. 60. Black Hill Study: OLD RED SANDSTONE ERRATICS CONCENTRATIONS.



Symbolism is as used previously on figs. 58 and 59 a measure of structural control in the form and position of this ridge must be suggested by such concentrations (56% and 43% respectively). Southwards towards the larger steeper feature previously suggested as having trachytic control in its stoss end, Old Red Sandstone counts drop to 20% although this is still relatively high in terms of surface concentrations. South-wards again towards the tails streaming off Redpath hill, a count of 42% Old Red Sandstone was recorded towards the up-ice margins of a long low form, again suggestive of, at least very shallow tills.

Old Red Sandstone concentrations on the Yarlside drumlin are also interesting. Counts of 20% plus are noted low on the stoss end of this feature, indicating shallow tills in an area where glacial erosion would have been particularly active around the obstruction provided by the small igneous body suggested previously. Values of 15% and 18% on the crest and tail respectively indicate Old Red Sandstone influence close to the surface in these areas also. Values of 6% and 13% in flank samples are entirely explicable in terms of short distance transport from these shallow till areas by basal ice curving around the drumlin.

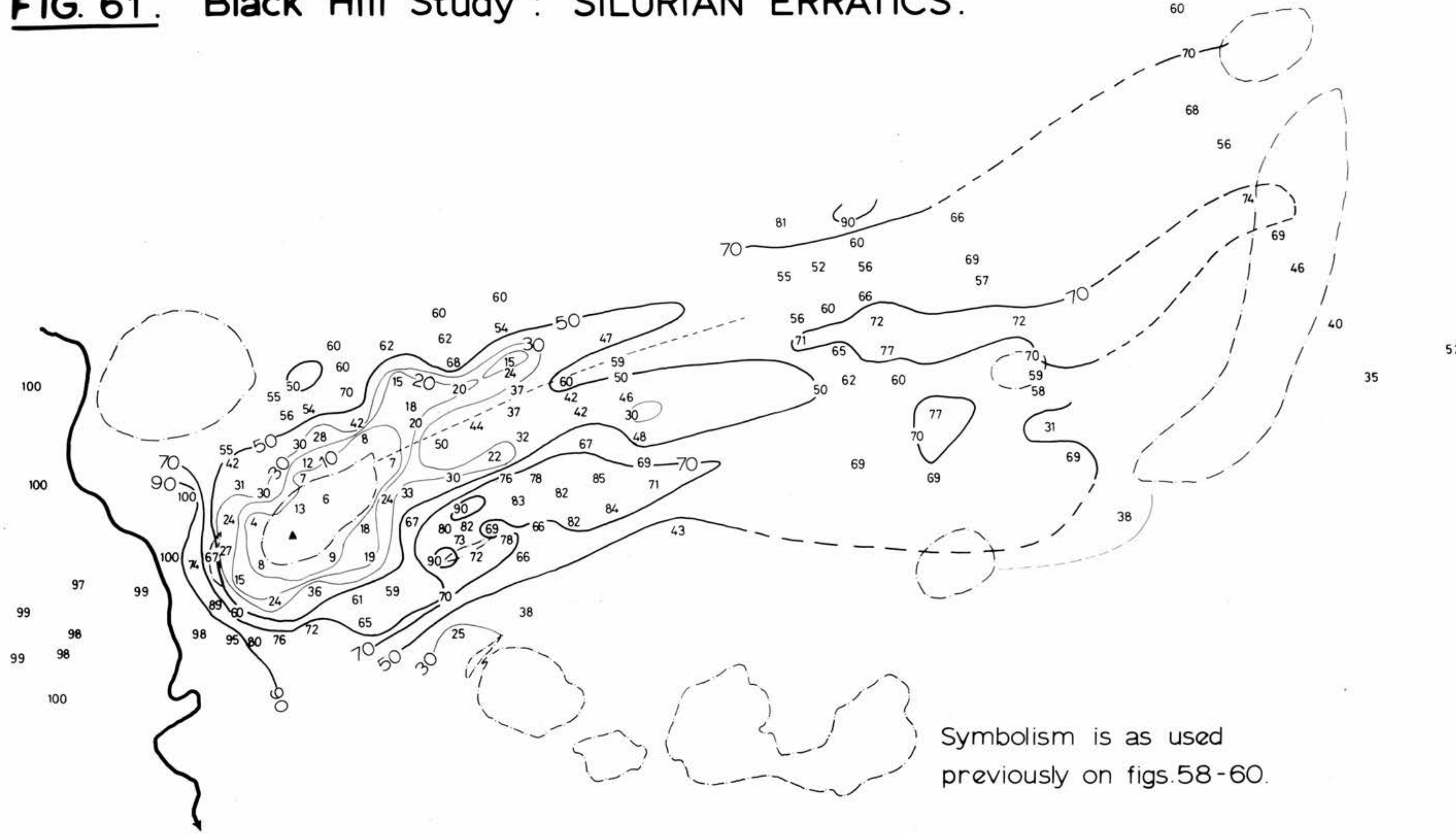
Because of the variable counts of the Old Red Sandstone erratics locally over the Old Red Sandstone area in response to local bedrock topography and because of the ubiquitous presence of this bedrock and its known susceptibility to rapid breakdown, during glacial transport, it is not possible to enlarge the Old Red Sandstone study to an examination of general erratics transport patterns from one side of the study area to the other.

<u>The Silurian erratics</u> The ubiquitous Silurian erratics dominate the macrofabrics of tills of the study area. This abundance of Silurian material is a result of the great extent of the Silurian strata located up-glacier of this area and its ability to survive considerable glacial

transport.

Only the highest parts of Black Hill and parts of the upper tail exhibited Silurian concentrations of less than 20%. Within the study area however there are two main situations in which Silurian erratics are particularly dominant, firstly in the ice-moulded topography between the higher crags and tails of the igneous bodies (Black Hill, White Hill, Redpath Hill, Brotherstone Hills and Mellerstain Hill), and secondly towards the east of the study area where tills become generally slightly deeper. The higher Silurian concentrations are therefore seen to be associated with two phenomena: with faster glacier streaming through the gaps in the intrusive rocks, and with the deeper tills where local bedrock influences are diminished. The latter areas are frequently recognisable by darker, browner tills compared with the more reddish tills of higher Old Red Sandstone influence, although conversely many tills of comparatively low Old Red Sandstone counts did show a pronounced reddish colour, confirming Old Red Sandstone influence in their finer grades.

FIG. 61. Black Hill Study : SILURIAN ERRATICS.



Symbolism is as used previously on figs. 58-60.

CHAPTER TEN

STATISTICAL TESTS ON LOCAL VERTICAL VARIATIONS IN TILL COMPOSITION

The purpose of the studies discussed in this chapter was

(a) to examine in more detail the vertical variations in till composition within 2m sections (as suggested previously in chapter 4), and to test statistically the data obtained, to find whether the apparent variations were significant or not,

(b) to examine any variations in concentrations of the major till components in relation to different size-ranges within the macro-fabric.

Samples were taken from 10 sites across the study area and details of the sites are given below.

SAMPLE 1 Oxenrig Farm NT849415 Carboniferous area. Site low on lee flank of large drumlin.

SAMPLE 2 Todrig Farm NT792422 Carboniferous area. Site high on drumlin crest, stoss end.

SAMPLE 3 Stainrigg Mains Farm NT778433 Carboniferous area. Site on wide, low ridge, slight flutings, low local relief.

SAMPLE 4 Bartlehill Farm NT772413 Carboniferous area. Site on low area between drumlins.

SAMPLES 5, 6 and 7 NT736419 Samples taken at 15m intervals in a line across direction of ice movement. Flat, sandstone-based ridge east of Hume village, Carboniferous area.

SAMPLE 8 Legars Farm NT719407 Down-ice limit of basalt bedlock. Site on wide tail feature.

SAMPLE 9 Fallsidehill Farm NT682417 Basalt bedrock area. Site on flank of wide ridge, local flutings.

SAMPLE 10 Coltcrooks Farm NT658409 Basalt/Old Red Sandstone
function. Site low on tail of locally fluted ridge.

Samples were collected using a power-driven auger of 30 cm diameter. The auger was driven in to the required depth and then extracted. The hole and auger were cleaned of all loose material. The auger was then driven in until it had collected sufficient material, the power switched off, and the auger extracted complete with sample. Care was taken to avoid collection of loose material from the side walls during extraction.

The maximum sample size was 11.5 kg, the minimum 6.3 kg with a mean of 8.5 kg. Six samples were taken at each site, sample A from a depth of 25 cm and subsequent samples at 35 cm vertical intervals down to sample F at 2m depth. Samples A, B, C, D, E and F thus occurred at depths of 25, 60, 95, 130 165 and 200 cm respectively. To avoid the situation whereby a whole sample might conceivably consist of one or two more massive erratics, a maximum stone size of 128 mm was set for sampling.

The collected samples were then taken into the laboratory, dried and broken down, then dry sieved into the following size ranges:

0- 2 mm	diameter
2- 4 mm	"
4- 8 mm	"
8- 16 mm	"
16- 32 mm	"
32- 64 mm	"
64-128 mm	"

The weight of each size-grouping was determined and all size groupings above 4 mm were retained for further study. 100 fragments were counted in each size grouping whenever possible but all fragments were counted if the total was below this number. Erratics were identified as belonging to either the four main erratics group of

Basalt, Silurian, Old Red Sandstone and Carboniferous or else an 'others' category which included all unidentified stones as well as various felsites, andesites, agglomerate etc.

During the physical breakdown of the samples it was apparent that certain less resistant erratics, particularly the sediments and many of the chemically weathered basaltic lavas, were liable to be destroyed. This was particularly so in some of the very compacted clay tills in samples D to F at sites 8 to 10. It is difficult to make any quantitative allowance for this phenomenon since the effect might take a variety of forms; a decrease in absolute numbers of given erratics; a lowering of mean size within a given erratic group or even a lesser percentage of a sample being registered in the finer grades due to attempts to protect such weaker erratics during break-down. It is suggested therefore that the following distributions of size-ranges within samples can not be completely accurate, that errors will be variable between samples, but that such errors would be unavoidable by any method. Considerable care was taken in the handling of samples in order to minimise this effect as far as possible.

STATISTICAL METHODS

Examination of the results was carried out using a development of the (χ^2) Chi-square test and an example of the amplication of this test is given below.

To apply the Chi-square test, the frequencies are first arranged in a 'k' x 'r' contingency table, (fig 1, below; where k = independent samples and r = discrete categories within these samples). The null hypothesis is that the 'k' samples of frequencies or proportions have come from the same population or from identical populations. This hypothesis, that the samples do not differ among themselves may be tested by using the formula $$X^2 = \sum_{i=1}^{r} \sum_{j=1}^{k} \frac{(Oij - Eij)^2}{Eij}$$

Where Oij = observed number of cases categorised in i'th row of

j'th column,

Eij = number of cases expected under Ho to be categorised in

i'th row of j'th column.

The degree of freedom for such a distribution can be calculated by the formula df = (k - 1) (r - 1) where k = number of columns and r = number of rows. Using the X^2 tables, if the result proves equal to or greater than the tabulated figure for the chosen level of significance and if df = (k - 1) (r - 1) then Ho (the null hypothesis) may be rejected at that level of significance. The acceptable level of significance adopted in this instance was the 95% level (p 0.05).

EXAMPLE

An examination of till composition at different depths at sample site 10. In this example the null hypothesis (Ho) would be that there was no significant difference in composition between the different samples (for the particular size-group being examined). A rejection of the null hypothesis would suggest that till composition showed significant variation at different depths at this site.

Site 10 Coltcrooks Farm site NT658409
4-8mm size range
Figures used are absolute numbers, not percentages.

Fig. (a)

SAMPLE	A	B	C	D	E	F	TOTAL
BASALT	10 ^{56}	34 $^{59.6}$	58 $^{58.4}$	83 $^{59.7}$	86 $^{60.3}$	82 ^{59}	353
SILURIAN	80 $^{31.7}$	58 $^{33.8}$	33 $^{33.1}$	12 $^{33.8}$	8 $^{34.1}$	9 $^{33.4}$	200
O.R.S.	1 $^{3.3}$	5 $^{3.5}$	4 $^{3.5}$	2 $^{3.5}$	4 $^{3.5}$	5 $^{3.5}$	21
TOTAL	91	97	95	97	98	96	574

$$X^2 = \sum_{i=1}^{r} \sum_{j=1}^{k} \frac{(Oij - Eij)^2}{Eij}$$

$$= \frac{(10-56)^2}{56} + \frac{(34-59.6)^2}{59.6} + \frac{(58-58.4)^2}{58.4} + \frac{(83-59.7)^2}{59.7} + \frac{(86-60.3)^2}{60.3}$$

$$+ \frac{(83-59)^2}{59} + \frac{(80-31.7)^2}{31.7} + \frac{(58-33.8)^2}{33.8} + \frac{(33-33.1)^2}{33.1} + \frac{(12-33.8)^2}{33.8}$$

$$+ \frac{(8-34.1)^2}{34.1} + \frac{(9-33.4)^2}{33.4} + \frac{(1-3.3)^2}{3.3} + \frac{(5-3.5)^2}{3.5} + \frac{(4-3.5)^2}{3.5}$$

$$+ \frac{(2-3.5)^2}{3.5} + \frac{(4-3.5)^2}{3.5} + \frac{(5-3.5)^2}{3.5}$$

$$= \underline{224.25}$$

For the data illustrated, $\chi^2 = 224.25$ with df = (k - 1) (r - 1) = (6 - 1) (3 - 1) = 10. This value of χ^2 is significant far beyond the 0.05 level. Indeed it is significant at the 0.001 level (99.9%). Since p 0.001 is less than one previously set level of significance (x = 0.05), our decision is to reject Ho. The conclusion is that till composition at different depths in site 10 is significantly different.

The following tables summarise the results of the significance tests. Results are marked as either significant or not significant at the 95% level (p 0.05). The degree of significance is indicated for all significant samples while in those non-significant samples marked with an asterisk, results indicated the null hypothesis to be applicable at the 95% level of probability.

TABLE A VARIATION IN TILL COMPOSITION WITH DEPTH

(NS : Not significant. Significance levels given for other samples.)

(i) 4-8mm SIZE RANGE

SITE 1	$p<0.01$	SITE 6	$p<0.005$
2	NS	7	$p<0.001$
3	NS	8	NS*
4	NS	9	$p<0.001$
5	$p<0.001$	10	$p<0.001$

(ii) 8-16mm SIZE RANGE

SITE 1	NS	SITE 6	$p<0.001$
2	NS	7	$p<0.001$
3	NS	8	$p<0.05$
4	NS	9	$p<0.001$
5	$p<0.001$	10	$p<0.001$

(iii) 16-32mm SIZE RANGE

SITE 1	NS	SITE 6	NS
2	NS	7	NS
3	NS*	8	NS
4	NS	9	$p<0.001$
5	NS	10	$p<0.001$

TABLE B VARIATION IN SIZE WITH DEPTH (using stones 4-32mm)

(i) BASALT ERRATICS

SITE 1	NS	SITE 6	NS*
2	NS	7	NS
3	NS	8	NS
4	$p<0.001$	9	NS
5	NS	10	NS

(ii) SILURIAN ERRATICS

SITE 1	NS*	SITE 6	NS*
2	NS	7	NS*
3	NS*	8	NS
4	NS	9	$p<0.05$
5	NS*	10	NS

TABLE C PERCENTAGE OF SAMPLE WEIGHT WITHIN GIVEN SIZE RANGES

1 SAMPLE	2 SAMPLE WEIGHT	3 % 0-2mm	4 % 2-4mm	5 % 4-8mm	6 % 8.16mm	7 % 16-32mm	8 % 32-64mm	9 % 64-128mm
1A	9.2kg	39.2	4.9	6.0	8.0	16.9	25.0	0
1B	11.5	43.4	7.9	8.4	10.9	13.9	15.5	0
1C	9.8	38.9	7.7	11.4	8.8	12.1	9.7	10.3
1D	9.2	42.8	9.5	10.0	6.8	9.4	15.5	6.0
1E	7.1	51.9	10.3	11.7	5.9	9.3	22.0	9.5
1F	9.4	39.9	8.5	8.3	4.6	6.2	21.8	10.8
2A	9.2	67.8	8.8	5.8	4.2	4.5	2.2	6.7
2B	7.6	46.7	15.4	18.2	9.9	5.3	4.6	0
2C	7.2	45.7	12.4	11.8	5.2	5.7	10.4	8.7
2D	7.3	34.8	11.3	11.1	5.1	9.5	14.0	14.2
2E	7.5	29.6	10.1	8.1	3.5	1.6	18.8	28.1
2F	8.2	43.1	9.2	8.6	7.0	9.2	16.0	6.6
3A	8.4	52.8	12.9	8.7	5.2	4.8	4.1	11.5
3B	8.4	48.1	13.7	13.6	10.8	6.4	7.4	0
3C	8.9	44.9	11.7	8.4	8.7	6.4	11.5	7.4
3D	7.8	38.2	8.7	12.1	4.9	7.5	16.5	12.1
3E	9.4	32.4	9.8	9.8	5.2	4.7	19.1	19.0
3F	11.4	43.7	8.4	10.8	2.2	2.4	12.7	19.8
4A	7.1	50.4	12.8	6.9	4.3	8.0	3.0	0
4B	7.0	60.0	16.9	7.9	4.3	4.7	6.2	0
4C	6.7	37.8	11.3	11.4	4.7	7.0	14.4	13.3
4D	7.9	57.8	11.9	7.7	2.9	4.3	15.3	0
4E	6.7	56.4	16.2	8.8	3.2	5.3	10.0	0
5A	8.7	60.4	10.1	8.1	3.1	2.1	2.2	8.0
5B	9.2	45.3	12.1	12.2	00.1	6.0	7.2	7.1

1	2	3	4	5	6	7	8	9
5C	7.8	48.1	15.1	18.0	7.4	8.1	3.3	0
5D	9.4	40.1	10.0	9.0	7.4	7.0	14.4	12.1
5E	10.9	33.1	9.1	12.4	4.1	2.0	18.0	21.2
5F	8.7	39.1	8.0	10.1	7.3	10.1	16.2	10.0
6A	7.4	54.0	12.3	8.1	11.3	10.2	4.1	0
6B	7.3	50.3	12.2	12.0	8.0	10.3	7.2	0
6C	7.4	41.7	13.4	11.1	8.5	8.2	17.1	0
6D	8.2	32.0	12.3	10.1	10.3	13.0	7.2	5.1
6E	8.7	35.4	10.0	14.1	5.1	6.0	17.3	12.1
6F	8.1	30.0	7.0	9.1	10.0	14.0	14.2	15.7
7A	7.1	58.2	10.0	10.4	14.2	4.1	3.1	0
7B	7.0	49.2	10.2	12.0	10.2	9.3	9.1	0
7C	7.4	48.1	10.0	7.4	8.3	10.1	16.1	0
7D	8.2	40.2	11.1	6.3	11.5	10.7	11.1	9.1
7E	10.1	30.1	9.1	7.0	11.7	10.7	17.3	14.1
7F	9.7	32.1	9.4	9.1	12.3	15.2	11.8	10.1
8A	8.8	58.0	6.5	3.6	4.7	7.0	6.1	14.0
8B	8.6	49.8	11.9	4.5	4.3	6.7	14.6	8.1
8C	7.1	49.4	11.3	6.3	3.6	4.1	1.5	23.8
8D	8.0	47.3	9.1	6.9	4.8	8.1	18.2	5.6
8E	6.5	52.9	10.8	5.8	4.4	5.9	10.8	9.4
8F	7.2	53.0	12.2	7.2	5.7	6.1	15.8	-
9A	9.1	63.9	8.2	9.1	8.1	7.4	3.4	0
9B	10.8	49.8	12.5	12.8	9.1	6.9	9.0	0
9C	11.3	36.4	13.1	14.5	10.9	9.6	15.5	0
9D	10.1	50.5	11.1	10.6	7.3	9.0	11.5	0
9E	8.5	40.1	12.7	14.5	10.3	9.1	13.1	0
9F	8.0	35.7	10.6	10.1	9.3	17.5	16.7	0

1	2	3	4	5	6	7	8	9
10A	8.9	60.2	6.4	10.2	6.8	10.4	6.4	0
10B	9.2	46.4	13.8	13.6	7.2	9.8	9.2	0
10C	9.1	35.2	14.7	15.7	12.6	8.8	13.6	0
10D	10.0	40.5	8.1	9.7	12.2	9.6	12.4	7.5
10E	9.9	38.2	11.7	16.1	11.2	10.6	11.2	0
10F	10.4	31.2	10.6	8.4	10.8	17.3	21.7	0

TABLE D COMPOSITE TABLES OF RESULTS

Results are expressed in the form illustrated below. Where the percentage weight column is left blank in any sample, then weight measurements were not taken in that sample at that particular size-range.

SAMPLE NO. and ERRATIC GROUP		4-8mm		8-16mm			16-32mm			32-64mm			64-128mm		
		No	%No	No	%Wt	%No	No	%Wt	%No	No	%Wt	%No	No	%Wt	%No
		A	B	C	D	E	F	G	H	I	J	K	L	M	N
1A BASALT	(B)	7	7	6	-	6	6	4	6	0	0	0	0	0	0
SILURIAN	(S)	84	84	89	-	89	87	94	91	20	88	95	0	0	0
O.R.S.	(O)	0	0	0	-	0	0	0	0	0	0	0	0	0	0
CARBONIF.	(C)	0	0	0	-	0	0	0	0	0	0	0	0	0	0
OTHERS	(X)	9	9	5	-	5	3	2	3	1	12	5	0	0	0
1B	B	5	5	2	1.1	2	4	4	5	2	8	10	0	0	0
	S	84	84	89	91	89	76	89	87	17	89	85	0	0	0
	O	4	4	0	0	0	0	0	0	0	0	0	0	0	0
	C	0	0	6	5	6	0	0	0	0	0	0	0	0	0
	X	7	7	3	3	3	7	7	8	1	3	5	0	0	0
1C	B	9	9	3	-	3	6	7	9	0	0	0 0	0	0	0
	S	81	81	90	-	90	54	89	83	6	92	86	2	100	100
	O	1	1	0	-	0	0	0	0	0	0	0	0	0	0
	C	2	2	0	-	0	0	0	0	0	0	0	0	0	0
	X	7	7	7	-	7	5	4	8	1	8	14	0	0	0

		A	B	C	D	E	F	G	H	I	J	K	L	M	N
1D	B	10	10	2	-	2	4	11	11	0	0	0	0	0	0
	S	73	73	87	-	87	28	81	76	9	100	100	1	100	100
	O	0	0	0	-	0	0	0	0	0	0	0	0	0	0
	C	7	7	1	-	1	0	0	0	0	0	0	0	0	0
	X	10	10	10	-	10	5	8	13	0	0	0	0	0	0
1E	B	7	7	2	-	2	3	5	7	3	19	23	1	100	100
	S	76	76	91	-	91	34	85	88	8	67	62	0	0	0
	O	0	0	0	-	0	0	0	0	0	0	0	0	0	0
	C	9	9	1	-	1	2	7	5	0	0	0	0	0	0
	X	8	8	6	-	6	2	3	5	2	14	15	0	0	0
1F	B	7	7	3	3	3	4	16	12	1	11	10	0	0	0
	S	74	74	90	91	90	27	82	82	9	89	90	1	100	100
	O	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	C	5	5	1	1	1	0	0	0	0	0	0	0	0	0
	X	14	14	6	6	6	2	2	6	0	0	0	0	0	0
2A	B	6	6	4	4	4	1	6	5	1	59	50	1	100	100
0	S	80	80	90	91	90	21	94	95	1	41	50	0	0	0
	O	2	2	0	0	0	0	0	0	0	0	0	0	0	0
	C	2	2	0	0	0	0	0	0	0	0	0	0	0	0
	X	10	10	6	5	6	0	0	0	0	0	0	0	0	0
2B	B	4	4	6	6	6	2	5	7	0	0	0	0	0	0
	S	80	80	83	83	3	23	88	86	2	100	100	0	0	0
	O	4	4	0	0	0	0	0	0	0	0	0	0	0	0
	C	2	2	7	7	7	2	7	7	0	0	0	0	0	0
	X	10	10	4	5	4	0	0	0	0	0	0	0	0	0
2C	B	4	4	3	3	3	1	10	4	0	0	0	0	0	0
	S	79	79	83	83	83	20	82	80	8	100	100	1	100	100
	O	3	3	0	0	0	0	0	0	0	0	0	0	0	0
	C	5	5	7	7	7	2	3	8	0	0	0	0	0	0
	X	9	9	7	7	7	2	5	8	0	0	0	0	0	0

		A	B	C	D	E	F	G	H	I	J	K	L	M	N
2D	B	7	7	3	-	3	4	5	8	1	7	10	1	100	100
	S	77	77	89	-	89	39	85	81	8	78	80	0	0	0
	O	1	1	0	-	0	0	0	0	0	0	0	0	0	0
	C	7	7	5	-	5	1	1	2	1	14	10	0	0	0
	X	8	8	3	-	3	4	9	8	0	0	0	0	0	0
2E	B	10	10	3	3	3	1	5	7	2	18	20	0	0	0
	S	71	71	83	83	83	12	86	79	7	70	70	4	100	100
	O	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	C	7	7	4	4	4	1	3	7	0	0	0	0	0	0
	X	12	12	10	10	10	1	5	7	1	12	10	0	0	0
2F	B	7	7	4	-	4	10	25	23	5	58	56	0	0	0
	S	68	68	83	-	83	26	64	60	3	34	33	1	100	100
	O	1	1	0	-	0	0	0	0	0	0	0	0	0	0
	C	9	9	5	-	5	3	3	7	0	0	0	0	0	0
	X	15	15	8	-	8	4	8	10	1	8	11	0	0	0
3A	B	6	6	6	5	6	6	33	20	0	0	0	0	0	0
	S	80	80	89	91	89	22	56	73	2	100	100	2	100	100
	O	2	2	0	0	0	0	0	0	0	0	0	0	0	0
	C	4	4	0	0	0	0	0	0	0	0	0	0	0	0
	X	8	8	5	5	5	2	11	7	0	0	0	0	0	0
3B	B	8	8	5	5	5	1	7	5	1	30	25	0	0	0
	S	79	79	84	85	84	18	87	86	3	70	75	0	0	0
	O	3	3	0	0	0	0	0	0	0	0	0	0	0	0
	C	0	0	2	2	2	0	0	0	0	0	0	0	0	0
	X	10	10	9	8	9	2	6	9	0	0	0	0	0	0
3C	B	9	9	7	-	7	4	15	15	2	27	40	1	100	100
	S	76	76	82	-	82	20	71	77	3	63	60	0	0	0
	O	2	2	0	-	0	0	0	0	0	0	0	0	0	0

		A	B	C	D	E	F	G	H	I	J	K	L	M	N
3C	C	3	3	4	-	4	0	0	0	0	0	0	0	0	0
	X	10	10	7	-	7	2	14	8	0	0	0	0	0	0
3D	B	7	7	8	-	8	3	10	13	2	24	25	0	0	0
	S	78	78	82	-	82	18	73	78	5	68	63	2	100	100
	O	3	3	0	-	0	1	7	4	0	0	0	0	0	0
	C	2	2	4	-	4	0	0	0	0	0	0	0	0	0
	X	10	10	6	-	6	1	10	4	1	8	12	0	0	0
3E	B	9	9	7	-	7	4	15	21	3	21	30	2	71	67
	S	76	76	80	-	80	12	71	63	6	69	60	1	29	33
	O	5	5	1	-	1	1	7	5	0	0	0	00	0	0
	C	1	1	7	-	7	0	0	0	0	0	0	0	0	0
	X	9	9	5	-	5	2	7	11	1	10	10	0	0	0
3F	B	7	7	8	-	8	3	19	13	2	24	22	1	20	23
	S	78	78	81	-	81	20	70	83	5	63	56	2	80	67
	O	2	2	0	-	0	0	0	0	0	0	0	0	0	0
	C	3	3	6	-	6	0	0	0	0	0	0	0	0	0
	X	10	10	5	-	5	1	11	4	2	13	22	0	0	0
4A	B	3	3	1	-	1	5	31	17	0	0	0	0	0	0
	S	83	83	76	-	92	21	64	72	3	100	100	0	0	0
	O	3	3	4	-	5	2	3	7	0	0	0	0	0	0
	C	4	4	0	-	0	0	0	0	0	0	0	0	0	0
	X	7	7	2	-	2	1	1	4	0	0	0	0	0	0
4B	6	6	4	4	-	0	0	0	0	0	0	0	0	0	0
	S	81	81	91	-	91	21	86	91	4	100	100	0	0	0
	O	5	5	3	-	3	1	13	4	0	0	0	0	0	0
	C	1	1	1	-	1	0	0	0	0	0	0	0	0	0
	X	7	7	1	-	1	1	1	4	0	0	0	0	0	0

		A	B	C	D	E	F	G	H	I	J	K	L	M	N
4C	B	6	6	1	-	1	1	2	4	0	0	0	0	0	0
	S	78	78	93	-	93	25	86	89	7	100	100	1	42	50
	O	3	3	2	-	2	0	0	0	0	0	0	0	0	0
	C	2	2	0	-	2	1	10	4	0	0	0	1	58	50
	X	9	9	4	-	4	1	2	4	0	0	0	0	0	0
4D	B	5	5	6	-	5	2	6	10	0	0	0	0	0	0
	S	79	79	96	-	89	17	81	85	5	74	71	0	0	0
	O	9	9	2	-	2	1	13	5	0	0	0	0	0	0
	C	1	1	0	-	0	0	0	0	1	18	14	0	0	0
	X	7	7	4	-	4	0	0	0	1	8	14	0	0	0
4E	B	7	7	3	-	3	2	5	9	0	0	0	0	0	0
	S	78	78	79	-	95	17	87	77	5	100	100	0	0	0
	O	9	9	2	-	2	0	0	0	0	0	0	0	0	0
	C	0	0	0	-	0	1	2	5	0	0	0	0	0	0
	X	6	6	1	-	1	2	6	9	0	0	0	0	0	0
4F	B	5	5	2	-	2	5	27	25	1	17	17	0	0	0
	S	82	82	72	-	93	14	64	70	5	83	83	0	0	0
	O	1	1	3	-	3	0	0	0	0	0	0	0	0	0
	C	1	1	0	-	0	0	0	0	0	0	0	0	0	0
	X	11	11	2	-	2	1	9	5	0	0	0	0	0	0
5A	B	12	12	15	-	15	4	17	13	0	0	0	1	100	100
	S	84	84	80	-	80	23	70	77	3	100	100	0	0	0
	O	2	2	0	-	0	1	7	3	0	0	0	0	0	0
	C	0	0	0	-	0	0	0	0	0	0	0	0	0	0
	X	2	2	5	-	5	2	10	7	0	0	0	0	0	0
5B	B	20	20	25	-	25	17	42	38	1	31	20	0	0	0
	S	72	72	69	-	69	24	40	53	4	69	80	1	100	100
	O	7	7	2	-	2	1	5	2	0	0	0	0	0	0

		A	B	C	D	E	F	G	H	I	J	K	L	M	N
5B	C	0	0	0	-	0	0	0	0	0	0	0	0	0	0
	X	1	1	4	-	4	3	13	7	0	0	0	0	0	0
5C	B	20	20	28	-	28	12	27	32	1	32	33	0	0	0
	S	63	63	58	-	58	20	60	53	2	68	67	0	0	0
	O	9	9	6	-	6	2	6	5	0	0	0	0	0	0
	C	5	5	2	-	2	0	0	0	0	0	0	0	0	0
	X	3	3	6	-	6	4	7	10	0	0	0	0	0	0
5D	B	17	17	20	-	20	15	30	32	3	19	30	1	70	50
	S	73	73	69	-	69	30	60	64	7	81	70	1	30	50
	O	5	5	4	-	4	0	0	0	0	0	0	0	0	0
	C	5	5	3	-	3	0	0	0	0	0	0	0	0	0
	X	0	0	4	-	4	2	10	14	0	0	0	0	0	0
5E	B	14	14	22	-	22	12	32	27	7	30	39	3	82	75
	S	65	65	61	-	61	27	54	60	8	50	44	1	18	25
	O	7	7	1	-	1	3	5	7	2	10	11	0	0	0
	C	11	11	12	-	12	0	0	0	0	0	0	0	0	0
	X	3	3	4	-	4	3	9	7	1	10	6	0	0	0
5F	B	17	17	18	-	18	20	27	30	6	40	38	2	100	100
	S	56	56	58	-	58	36	60	55	8	47	50	0	0	0
	O	4	4	0	-	0	4	5	6	1	5	6	0	0	0
	C	20	20	17	-	17	0	0	0	1	8	6	0	0	0
	X	3	3	7	-	7	6	9	9	0	0	0	0	0	0
6A	B	13	13	18	-	18	14	29	30	0	0	0	0	0	0
	S	83	83	77	-	77	28	63	60	3	100	100	0	0	0
	O	1	1	0	-	0	0	0	0	0	0	0	0	0	0
	C	0	0	0	-	0	0	0	0	0	0	0	0	0	0
	X	3	3	5	-	5	5	8	11	0	0	0	0	0	0

		A	B	C	D	E	F	G	H	I	J	K	L	M	N
6B	B	23	23	25	-	25	17	39	35	2	35	29	0	0	0
	S	68	68	66	-	66	31	58	63	5	65	71	0	0	0
	O	4	4	5	-	5	0	0	0	0	0	0	0	0	0
	C	0	0	0	-	0	0	0	0	0	0	0	0	0	0
	X	5	5	4	-	4	1	3	2	0	0	0	0	0	0
6C	B	24	24	24	-	24	19	30	35	6	51	40	0	0	0
	S	60	60	65	-	65	32	65	58	8	41	53	0	0	0
	O	8	8	6	-	6	0	0	0	0	0	0	0	0	0
	C	4	4	2	-	2	0	0	0	0	0	0	0	0	0
	X	4	4	3	-	3	4	5	7	1	8	7	0	0	0
6D	B	18	18	20	-	20	19	40	34	2	51	40	0	0	0
	S	67	67	67	-	67	33	51	59	3	49	60	1	100	100
	O	9	9	7	-	7	0	0	0	0	0	0	0	0	0
	C	1	1	4	-	4	1	4	2	0	0	0	0	0	0
	X	5	5	2	-	2	3	5	5	0	0	0	0	0	0
6E	B	20	20	19	-	19	17	31	28	5	35	29	2	100	100
	S	70	70	65	-	65	33	55	54	9	55	53	0	0	0
	O	2	2	2	-	2	1	4	2	2	6	12	0	0	0
	C	5	5	9	-	9	4	4	7	1	4	6	0	0	0
	X	3	3	5	-	5	6	6	10	0	0	0	0	0	0
6F	B	19	19	20	-	20	15	30	37	4	20	24	1	62	50
	S	67	67	62	-	62	22	59	54	11	70	65	1	38	50
	O	2	2	0	-	0	0	0	0	0	0	0	0	0	0
	C	9	9	14	-	14	2	5	5	0	0	0	0	0	0
	X	3	3	4	-	4	2	6	5	2	10	12	0	0	0
7A	B	15	15	20	-	20	19	39	34	0	0	0	0	0	0
	S	80	80	77	-	77	31	50	55	2	100	100	0	0	0
	O	0	0	0	-	0	0	0	0	0	0	0	0	0	0

		A	B	C	D	E	F	G	H	I	J	K	L	M	N
7A	C	0	0	0	-	0	2	6	4	0	0	0	0	0	0
	X	5	5	3	-	3	4	5	7	0	0	0	0	0	0
7B	B	18	18	21	-	21	10	27	22	1	29	20	0	0	0
	S	74	74	72	-	72	30	58	65	4	71	80	0	0	0
	O	5	5	4	-	4	2	5	4	0	0	0	0	0	0
	C	0	0	0	-	0	0	0	0	0	0	0	0	0	0
	X	3	3	3	-	3	4	10	9	0	0	0	0	0	0
7C	B	18	18	18	-	18	12	22	27	3	42	30	0	0	0
	S	64	64	69	-	69	25	60	56	6	50	60	0	0	0
	O	9	9	7	-	7	4	6	9	0	0	0	0	0	0
	C	5	5	3	-	3	0	0	0	0	0	0	0	0	0
	X	4	4	3	-	3	4	12	9	1	8	10	0	0	0
7D	B	13	13	18	-	18	10	14	25	4	52	40	1	100	1100
	S	75	75	71	-	71	24	72	63	4	32	40	0	0	0
	O	7	7	5	-	5	1	5	3	0	0	0	0	0	0
	C	2	2	5	-	5	1	3	3	1	6	10	0	0	0
	X	3	3	1	-	1	4	6	10	1	10	10	0	0	0
7E	B	9	9	16	-	16	11	19	22	7	51	44	2	71	67
	S	74	74	71	-	71	30	65	60	7	37	44	1	29	33
	O	3	3	1	-	1	2	4	4	0	0	0	0	0	0
	C	10	10	9	-	9	2	4	4	2	12	13	0	0	0
	X	4	4	3	-	3	5	8	10	0	0	0	0	0	0
7F	B	20	20	17	-	17	14	36	31	4	30	40	1	72	50
	S	63	63	64	-	64	24	44	53	3	44	30	11	28	50
	O	4	4	0	-	0	0	0	0	0	0	0	0	0	0
	C	13	13	15	-	15	4	9	9	1	8	10	0	0	0
	X	0	0	4	-	4	3	11	7	2	18	20	0	0	0

		A	B	C	D	E	F	G	H	I	J	K	L	M	N
8A	B	30	30	43	-	43	28	74	76	2	83	67	1	100	100
	S	53	53	46	-	46	8	24	22	1	17	33	0	0	0
	O	9	9	4	-	4	0	0	0	0	0	0	0	0	0
	X	8	8	7	-	7	1	1	2	0	0	0	0	0	0
8B	B	29	29	46	-	46	19	73	59	7	76	64	1	100	100
	S	54	54	43	-	43	7	14	22	4	24	36	0	0	0
	O	9	9	6	-	6	3	9	9	0	0	0	0	0	0
	X	8	8	5	-	5	3	4	9	0	0	0	0	0	0
8C	B	35	35	45	44	45	12	80	71	0	0	0	2	100	100
	S	52	52	50	51	50	5	20	29	1	100	100	0	0	0
	O	10	10	0	0	0	0	0	0	0	0	0	0	0	0
	X	3	3	5	5	5	0	0	0	0	0	0	0	0	0
8D	B	32	32	33	42	41	28	70	72	6	81	75	1	100	100
	S	53	53	42	46	46	9	26	23	1	4	13	0	0	0
	O	11	11	3	3	3	0	0	0	0	0	0	0	0	0
	X	4	4	9	9	10	2	4	5	1	5	13	0	0	0
8E	B	33	33	50	63	58	16	84	80	4	83	80	1	100	100
	S	51	51	32	31	35	2	12	10	1	17	20	0	0	0
	O	10	10	1	1	1	0	0	0	0	0	0	0	0	0
	X	6	6	5	6	6	2	4	10	0	0	0	0	0	0
8F	B	38	38	38	-	36	22	81	81	7	95	88	0	0	0
	S	50	50	62	-	59	4	17	15	1	5	12	0	0	0
	O	11	11	2	-	2	0	0	0	0	0	0	0	0	0
	X	2	2	3	-	3	1	2	4	0	0	0	0	0	0
9A	B	5	5	7	-	7	5	17	10	1	36	33	0	0	0
	S	80	80	88	-	88	38	76	79	2	64	67	0	0	0
	O	10	10	3	-	3	0	0	0	0	0	0	0	0	0
	X	5	5	2	-	2	5	7	10	0	0	0	0	0	0

		A	B	C	D	E	F	G	H	I	J	K	L	M	N
9B	B	47	47	64	-	64	40	70	68	6	100	100	0	0	0
	S	38	38	23	-	23	16	26	27	0	0	0	0	0	0
	O	12	12	4	-	4	2	2	3	0	0	0	0	0	0
	X	3	3	9	-	9	1	1	2	0	0	0	0	0	0
9C	B	61	61	89	-	89	52	83	88	14	100	100	0	0	0
	S	25	25	9	-	9	6	16	10	0	0	0	0	0	0
	O	13	13	2	-	2	0	0	0	0	0	0	0	0	0
	X	1	1	0	-	0	1	1	2	0	0	0	0	0	0
9D	B	77	77	91	-	91	53	80	90	9	85	90	0	0	0
	S	14	14	6	-	6	4	14	7	1	15	10	0	0	0
	O	5	5	2	-	2	1	2	2	0	0	0	0	0	0
	X	4	4	1	-	1	1	4	2	0	0	0	0	0	0
9E	B	79	79	90	-	90	60	90	88	9	91	90	0	0	0
	S	11	11	9	-	9	8	10	12	0	0	6	0	0	0
	O	6	6	0	-	0	0	0	0	0	0	0	0	0	0
	X	4	4	1	-	1	0	0	0	1	9	10	0	0	0
9F	B	82	82	86	-	86	76	86	94	13	88	87	0	0	0
	S	8	8	14	-	14	5	14	6	2	12	13	0	0	0
	O	7	7	0	—	0	0	0	0	0	0	0	0	0	0
	X	3	3	0	-	0	0	0	0	0	0	0	0	0	0
10A	B	10	10	10	-	10	5	14	12	1	24	25	0	0	0
	S	80	80	8	-	83	32	74	78	3	76	75	0	0	0
	O	1	1	3	-	3	1	2	2	0	0	0	0	0	0
	X	9	9	4	-	4	3	10	7	0	0	0	0	0	0
10B	B	34	34	40	-	40	17	37	33	3	54	60	0	0	0
	S	58	58	52	-	52	29	50	57	2	46	40	0	0	0
	O	5	5	2	-	2	1	4	2	0	0	0	0	0	0
	X	3	3	6	-	6	4	9	8	0	0	0	0	0	0

		A	B	C	D	E	F	G	H	I	J	K	L	M	N
10C	B	58	58	62	-	62	31	63	60	4	60	57	0	0	0
	S	33	33	30	-	30	13	20	25	2	29	29	0	0	0
	O	4	4	2	-	2	4	5	8	0	0	0	0	0	0
	X	5	5	6	-	6	4	12	8	1	11	14	0	0	0
10D	B	83	83	90	-	90	31	73	66	5	80	71	1	100	100
	S	12	12	7	-	7	9	10	19	1	6	14	0	0	0
	O	2	2	0	-	0	2	6	4	0	0	0	0	0	0
	X	3	3	3	-	3	5	11	11	1	14	14	0	0	0
10E	B	86	86	98	-	98	40	74	67	5	75	63	0	0	0
	S	8	8	2	-	2	7	9	12	2	15	25	0	0	0
	O	44	4	0	-	0	4	7	7	0	0	0	0	0	0
	X	2	2	0	-	0	9	10	15	1	10	12	0	0	0
10F	B	82	82	95	-	95	41	80	82	9	57	64	0	0	0
	S	9	9	6	-	4	7	18	14	3	30	21	0	0	0
	O	5	5	0	-	0	1	1	2	0	0	0	0	0	0
	X	4	4	1	-	1	1	1	2	2	13	14	0	0	0

Examination of the results

In order to verify the conclusions in chapters 4 to 6 a statistical examination of variations in till composition with depth was made. General findings appear to confirm trends discussed in those earlier chapters although in this instance closer vertical sampling intervals were adopted and erratics were examined within different size ranges.

All results are expressed in terms of erratics numbers and not weights. Meausurements of both weight and numbers in several earlier studies confirmed that results, particularly in the finer grades, were virtually similar, while it will be suggested subsequently that results in the coarser grade (32mm plus) should not be included in statistical treatment in this instance.

The major findings of earlier studies, which appear to be confirmed by the current study are as follows. Firstly there is an apparent increase in Silurian erratics towards the surface till in any section and a corresponding fall in the influence of local stones. Secondly, this trend is also visible on the more homogeneous tills of the Carboniferous bedrock area where Silurian influence remains high throughout a 2m section and vertical differences are less marked compared with thinner tills elsewhere. (The significance of these findings in terms of the processes of glaciation and deglaciation of the area has already been fully discussed.)

Site 8 provides the only apparent anomaly in the 10 sites examined. Earlier studies had suggested that a surface basalt concentration of over 40% would indicate basalt bedrock to lie with c. 1.5m of the surface. Studies from sites 9 and 10 in this series and from the area of the main basalt ridge in the pipeline associated studies appear to confirm this. At site 8 however basalt counts rise to around 50% plus in 8E although varying widely between different size-groupings, being markedly higher in the coarser grades, (Table D). In samples of tills recently incorporated into ice it has been suggested that initial increases are most marked in the coarser grades (Dreimanis and Vagners, 1969) and this would appear to be the most likely explanation in this instance. It is suggested that site 8 is an area of prolonged till accretion existing locally within the basalt area, producing a fairly uniform till with only a very slight rise in Silurian erratics towards the surface.

An extra dimension was added to this study in that the trends outlined above were also examined in relation to the size of erratics involved to ascertain whether such trends were uniformally applicable to all size-fractions of a given erratic group. In this instance however results in certain size ranges are inconclusive. The small numbers of erratics sampled in the larger size groupings (32 - 128mm) mean that considerable fluctuations in results occur on the basis of a difference of one or two erratics. It is suggested that the samples did not yield sufficient quantities to validate inclusion of these larger-size-groupings in any statistical treatment. In the 32 -64mm size range for example, 37 out of 60 samples yielded less than 10 ~~64-~~ stones and the mean sample size was only 8.4. In the 64- 128mm group there were 29 zero counts and the mean sample size was less than one. Accordingly, statistical examination involving size groupings only involves sizes between 4mm and 32mm.

The major findings of the statistical examination were (a) that the geological composition of the till varies significantly with depth and (b) that the percentage size particles of each geology do not vary with depth. Within these general trends variations did occur however.

Variations in till composition with depth (Table A)

The results reflect tills from different areas and may be grouped as follows:

Sites 1 to 4 are typical of the deeper, more homogeneous Silurian-dominated tills of the Carboniferous area.

Sites 5, 6 and 7 lie in the leeeof the basalt lavas and show increased basaltic influence at certain levels.

Site 8 has already been suggested as apparently anomalous yet representing an area of prolonged till accretion in a local pocket within the basaltic area.

Sites 9 and 10 lie close to basaltic bedrock and show the typically rapid vertical compositional changes associated with thinner tills.

At sites 1 to 4, although surface samples tend generally to show slightly higher Silurian counts compared with those at depth, differences are small and trends not always consistent over the profile. Statistical tests indicate that such differences are not significant enough to suggest that all samples might not have come from the same or identical tills. Only in the 4-8mm range at site 1 was a significant variation over the profile indicated. At three other sites however, two in this same size range, there was a 95% probability that the samples were derived from the same till. Such findings do not invalidate earlier ideas in any way, although suggesting that the slight observable differences do not satisfy statistical requirements. The consistency of Silurian increases, in surface tills (however small) has already been pointed to as significant evidence in this respect.

Sites 5, 6 and 7 however, show a different pattern particularly in the 4-8mm and 8-16mm fractions. Till composition is indicated to change significantly within the vertical extent of the section. These changes are typical of the compositional changes fully discussed in chapters 4 to 6, particularly the gradual dominance of Silurian erratics over more local stones towards surface tills. Results from the 16-32mm range were less significant. Possible interpretations of this might involve the lesser numbers of the weaker sedimentary erratics found in this range throughout the profile and the relatively greater importance of the newly incorporated basalts in these coarser grades.

The anomalous position of site 8 in the patterns of vertical compositional change has already been discussed although it will be noted (Table A) that significant variation was found in the 8-16mm range ($p<0.05$). This change does not indicate a regular pattern however but appears to be derived from quite marked fluctuations with the profile.

Sites 9 and 10 yielded very high Chi-Square values at all levels of size and the compositional changes involved are typical of a number of similar sites on thinner tills discussed in earlier chapters. Statistical tests thus confirm the very clear trends noted within sections of these thinner tills. It is suggested that in the deeper tills, of the Carboniferous area in particular, although statistical tests suggest that differences are not significant, the consistency of the increased Silurian counts in surface tills and the associated decline in more local erratics, however slight, is important evidence in confirming the more exotic origins of this material (chapters 4 to 6).

Variations in size with depth (Table B)

Silurian and basalt erratics were examined independently, these being the only groups yielding erratics in sufficient quantity for examination. Results of this study generally suggested that there was no significant change in the percentages of the different size ranges with depth. Only in sample 4 (Silurian) and sample 9 (Basalts) was significant variation suggested with depth. In neither case were consistent trends recognisable within the section. In 6 out of the 20 tests carried out in this series, results suggested adoption of Ho at the 95% level of probability. It seems therefore that no relationship may be inferred between particle size and depth. (It should be emphasised however that these studies only involved particles up to 32mm diameter.)

ADDENDUM p184.

Additional work on the statistical examination of erratics trends within sections (chapter 10) made no new contribution to theories outlined in previous chapters, generally tending merely to confirm earlier results. Accordingly no specific reference is made to this statistical analysis in the course of the final summary and discussion chapter.

RJ Kerr

CHAPTER ELEVEN

DISCUSSION AND SUMMARY

Introduction

The present study is apparently involved with a single till sequence deposited by one large ice sheet whose limits cannot be traced anywhere within the confines of the Tweed basin. Towards the coast and outside the present study area the Tweed ice was deflected southwards (e.g. up the till valley (Clapperton, 1967) by ice that had previously issued from the Central Lowlands of Scotland. On its other flank, the Tweed ice according to Clapperton, merged with ice nourished on the high ground culminating in the Cheviot. The high ground west of the Cheviot also appears to have been a source of ice (Clapperton, 1967, 1968). The major source of the Tweed ice, however lay to the west and south-west of the present study area.

The thickness of the Tweed ice is uncertain. Analogy with idealised simple ice-sheets suggests a figure of the order of 2,000m. However, this estimate may well be too high since more than one area of dispersal existed.

Till thickness varies considerably in the study area. The deepest tills occur on the Carboniferous bedrock area but deep exposures are scarce in this area. In one borehole near Stonefolds Farm, 8.2m of till overlay a bed of gravel 0.65m thick, which in turn covered a further 3.8m of till lying on bedrock (Manson, 1933). This along with some evidence of stratified drift incorporated into later drumlinoid forms (Clapperton, 1968), is one of the few indications of a possible previous glacial phase. Clapperton (1967) noted till depths up to 20m in sections along the Shipley burn south-east of the author's study area and other evidence from Northumberland as well as from Durham (Carruthers, 1939, 1947, 1953; Beaumont, 1971) also indicates widespread deposition of thick tills.

ICE STAGNATION

There is considerable evidence for ice stagnation and melting *in situ* in the study area. This can be summarised as follows.

(i) There are no moraines recording halt or retreat stages to be found in the basin (Sissons, unpubl.). Indeed no major halt phase has been firmly identified, within the limit of the last ice sheet in Yorkshire.

(ii) There is evidence of considerable movement of meltwaters in the inter-drumlin depression marking the last phases of ice wastage. There is no pattern to the meltwater channels and fluvioglacial deposits, either locally or regionally, to suggest active ice-marginal retreat.

(iii) There is evidence of large ice bodies controlling melt-out in some localities (Clapperton, 1967, 1968; Sissons, unpubl.).

(iv) Many fluvioglacial deposits are not associated with distinctive landforms and many are intimately associated with till. Such relationships provide important evidence in the case for melt-out tills. (Their occurrences were detailed in Chapter 2 and Figs. 15a to 15d.)

(v) Some very large meltwater channels (e.g. the Leat Water channel), cut obliquely across the drumlin field, implying superimposition of meltwater rivers from the ice completely across the underlying relief trends.

Ice stagnation may perhaps have been expected to produce a more widespread occurrence of surface fluvioglacial forms but this is not necessarily so. Before final stagnation occurred much deposition of till would have taken place from thinning, slowing ice with much of the englacial debris load gradually being lowered towards the glacier bed. By the time stagnation occurred the ice would have thinned, considerably with high debris concentrations locally within the basal ice, while englacial meltwater systems, already established, would have continued to develop as they dissipated the increased quantities of top-melt water. Much basal melting of debris is considered to have occurred as squeeze melt with gradual concentration of meltwaters into a number of major arteries of movement, represented today by the sub-surface fluvioglacial sequences (Figs. 15a-15d).

MELT-OUT TILLS AND SUB-SURFACE FLUVIOGLACIAL SEQUENCES

A modification of the ideas of Carruthers on melt-out tills appears applicable to the Tweed basin. It has been suggested previously that the relationships of certain tills to underlying sand and gravel sequences allied to fabric and particle-size comparisons between these upper tills and supposed lodgement tills, show the existence of tills deposited by slow squeeze-melt from stagnant ice. The full extent of the occurrence of these melt-out tills is less certain since in many instances they exhibit characteristics more commonly associated with lodgement till and may thus have escaped recognition in some sections.

The critical relationships between these melt-out tills and the relevant sand and gravel sequences were discussed in Chapter 2 and illustrated in Figs. 15a to 15d. Particularly significant is the section shown in Fig. 15d, an illustration from the tail of Knock Hill (NT 616441) which appears to confirm lack of ice movement subsequent to formation of the sand and gravel sequences. Collapse structures noted in other sections are taken to indicate subsequent melt-out of ice incorporated into the deposits (possibly from roof collapse) during deposition.

The possibility of cavity development in the lee of obstructions has been tentatively suggested as a potential area of development for some of the more striking fluvioglacial formations but this is not a necessary pre-requisite. Gradual squeeze-melt could in itself produce concentrations of water sorted debris into a few major arteries of movement, leading probably to the major channels, and as long as meltwater could be expelled laterally by such systems, the overlying till deposits could accumulate with minimum fabric disturbance. Ice in which a large amount of debris was concentrated may itself have resisted melting: sands accumulated beneath till, and the clean contact between the upper limit of the sand lenses and the lower limit of the surface till in Fig. 15d tend to support such a possibility. On a small scale this may locally be associated with the formation of clean regelation ice in the lee of local obstructions on the glacier bed. On stagnation this clean ice might melt before its cover of dirty ice, which would tend to resist melting (Boulton, 1975). Recent work (Boulton and Dent, 1974) has also shown that slowing debris-rich basal ice deforms much less readily than clean ice, and shearing in the basal layers might conceivably produce relative stagnation of this ice even before the final cessation of glacier movement.

The situation is a very delicate one in that an inefficient removal of meltwater could produce saturated tills in which injection features or even flowtill might be expected to occur. The latter could conceivably have occurred undetected in the sections examined but there was no evidence of either. The water transmissibility of the bed was probably an important factor in this situation.

The heat for such a melt-out mechanism may initially have come from the controlled release of geothermal heat and from a degree of pressure-melting or small-scale regelation heat transfer. Climatic amelioration would have had less effect on bottom-melt until meltwater percolation began to reach basal ice as the glacier thinned. The idea of ablation, tills generally presupposes some degree of top-melt but it is not envisaged as a major mechanism in this instance. Top-melt of essentially clean ice appears to have produced few if any positive features over much of the study area.

The work of Carruthers (1939, 1947, 1953) on tills approximately contemporaneous with those of the Tweed basin yielded results slightly different from those of the author's work, particularly in the order of the melt-out sequences, although the mechanics of deposition envisaged do not seem significantly different. No fine shear clays were noted in the Tweed area for example, and in none of the Tweed examples does the regular vertical sequence from fine to coarse upwards occur as envisaged by Carruthers.

Although the evidence presented above clearly indicates a till that technically may be termed an ablation till rather than lodgement till, this melt-out till cannot be immediately identified as ablation material. Drake (1974) in examining more typically accepted ablation and basal tills in New Hampshire found two tills with very marked differences in a number of their properties.

The basal till exhibited strong macrofabrics, a lack of "washing" in particle-size analyses and yielded less angular and more flattened pebbles than the ablation till. The latter showed weakly developed, inconsistent fabrics not parallel to striae or topographic trends, showed evidence of "washing" in mechanical analysis and yielded angular equidimensional pebbles. Such marked differences are not apparent in this instance.

No appreciable differences were detected in erratic content or stone shape in the two types of till recognised in the Carboniferous area although shape was not measured in detail. In two out of three sites examined (both in the Carboniferous bedrock area) particle size analyses did yield differences in the amount of clay present, with the clay content of surface tills being up to 20% lower than that of the basal samples. Silt percentages were less consistent, being up by 5% and down by 8% in the two surface samples while sand fractions were higher by up to 26% in surface tills. Some squeeze-washing of the upper tills may be envisaged to explain these differences but the well-developed fabric patterns maintained by the surface tills during melt-out suggest that disturbance was minimal. Since these surface tills overlie sand and gravel sequences which today act as very effective drainage systems within the soil, it may be that some of this disappearance of clays, assuming their existence in the first place, occurred post-glacially due to the very well-drained soil above the fluvioglacial sequences. Boulton and Dent (1974) have examined lodgement tills as they were exposed by glacier retreat and have recorded changes in the immediate post-depositional phase which greatly affected results of mechanical analyses on these tills, in particular, a 10-20% decrease in the fine fraction in the upper 20 cm of till. Such a process may have operated to greater depth in the Tweed area wherever fluvioglacial routeways were available for the removal of sub-surface meltwaters.

A third site examined by mechanical analysis in the Old Red Sandstone bedrock area, however, yielded highest clay percentages in the surface till, a known melt-out till. In this instance, lithological variations in the different erratic groups dominant at different levels in the section clearly explain such an occurrence. Till macro-fabric analyses in the Old Red Sandstone area again yield evidence of fabrics inherited from the transportational environment being maintained during melt-out (Chapter 2).

While the part of this study associated with the pipeline section did yield considerable evidence of the relationships between the fluvioglacial sequences and the overlying melt-out tills, there are a number of questions that need to be considered before the sequences are interpreted. Since these sequences represent lines of water movement within a general drift sequence, it would be desirable in future work to examine more fully their extent within any given area, and in particular their relationship to the streamlined forms of the area and the surface meltwater features. It is suggested as particularly desirable to record the pattern of their occurrence and origins on even one large drumlin, to examine their apparent relationship with tail locations, and to examine the apparent system of routeways that developed in preference to a general sheet of lesser, vertical amplitude. Simple augering is not feasible owing to the depth and nature of the sequences and their overburdens: therefore tracing is difficult other than by elaborate trenching or perhaps some application of seismic techniques . Consolidation tests on the overlying tills might also contribute to their understanding in leading to estimates of ice thickness at the time of till deposition. For example, in his work on melt-out tills Harrison (1957) suggested ice about 90 m in thickness. Such tests might also be applied more widely to measure the full extent of melt-out tills.

In previous chapters it was frequently suggested that since melt-out tills are not readily differentiated from lodgement tills, and since melt-out tills had been confirmed at various points throughout the study area, the extent of these might be greater than previously proposed. This is difficult to ascertain but it is tentatively suggested that it is un-necessary to envisage a complete mantle of melt-out material. Recent work, both empirical and theoretical (e.g. Boulton, 1975), has pointed to the creation of debris-rich streams within the basal ice, particularly where sizable obstructions exist on the glacier bed. Instead of debris concentrations in the basal ice measurable in centimetres, Boulton indicates debris-charged basal ice of 2 m depth created by plastic flow around these obstacles. As the glacier ice thinned and slowed, much of this material may have been deposited over a relatively short period as lodgement till but equally when final stagnation occurred it would be in these areas that maximum debris would still be available within the ice for the creation of the sequences discussed above. It will be suggested subsequently that these ice streams may have a significance on a wider regional scale in their influence on drumlin formation and patterns, but locally it is also probable that in the final stages of ice movement these debris-rich basal layers with their increased rigidity could have been over-ridden by shearing of the clearer ice with in situ melting proceeding slowly even at this stage. The provision of these streams of debris-rich ice could therefore have produced during final melt-out, a pattern of melt-out tills that shows quite localised variations in development. It is perhaps significant that the fullest developments of the sub-till fluvioglacial systems were noted on the lee flanks of two of the most imposing ice-moulded forms in the study area.

TILL FABRICS and TILL DEPOSITION

The analysis of till macrofabric patterns did not provide a means of differentiation of melt-out and lodgement tills but fabric analysis in general provided a comprehensive pattern of results. Weaker fabrics in some instances may be partially explicable in the extreme rounding of many stones, particularly some of the ubiquitous Silurian erratics, making them less conducive to the maintenance of an alignment (Drake, 1974) while others may have undergone subsequent modification due to post-glacial movement. The low angle of dip of many of the stones was an important aspect of the Tweed fabrics and it was suggested in Chapter 8 that measurement relative to surface slope might have been more relevant rather than to the horizontal. Most slopes at fabric sites were below c.5 or 6° however and analyses of 5 sites relative to the slope did not alter results appreciably. In an examination of till macro-fabrics as an indicator of mode of deposition it is difficult in this instance to divorce the mechanics of till deposition from those of drumlin formation (see later).

The overall fabric pattern clearly shows a movement of ice across the study area from the west and south-west, with fabrics closely related locally to other directional indicators, particularly drumlins. It is suggested that the bulk of the fabric pattern was inherited within the transportational environment. There are several lines of evidence to support this. Firstly, there is the marked similarity of fabric details between known melt-out tills and the author's so called "basal tills". Secondly, and one of the major factors of similarity referred to above, there is the marked development of the transverse peak in many fabrics, (Fig. 49). Thirdly, there is the theoretical, observational and experimental work in the literature. Laboratory experiments (Glen, Donner and West, 1957) and field tests (Holmes, 1941; Boulton, 1972) suggest that protracted flow is likely to develop a transverse peak: Boulton has recorded such a peak in narrow till bands within active ice and has suggested that this may be partly related to the collision of suitably shaped stones. Drake (1974) suggested that some well-rounded stones tend to roll more easily about their 'a' axis and thus develop a transverse orientation but in the Tweed area the transverse peak is so well developed (even on areas of lower Silurian influence where rounded stones are fewer in number), that stone shape is likely to be only a minor contributory factor. Boulton's observations on currently developing tills in Spitzbergen also showed that a plastering-on process was most likely to develop a parallel peak. Many workers (eg. Wright, 1957; Boulton, 1968, 1972) have supported Harrison's ice-shear theories in which a pronounced up-glacier dip was developed in fabrics in the transportational environment but were more dubious of the maintenance of this during deposition. It is suggested that the melt-out and fabric evidence from the Tweed area indicate a considerable fabric maintenance during deposition. If modification occurred it is most likely to have been in the parallel plane, i.e. as it affects angles of dip. It is suggested that some modification in this plane may have occurred in the Tweed area, both in the melt-out tills but also conceivably in tills being deposited quickly from active debris-rich ice. The net effect was to produce tills in which preferences within the parallel peak are often so slight as to cast serious doubts on the value of dominant dip direction as an indicator of the direction of glacier movement. Such results are in accord with the doubts expressed earlier by workers such as Holmes (1941), Donner and West (1957) and Penny and Catt (1967).

The fabrics examined here deal essentially with the upper parts of tills that are often thick, particularly on the Carboniferous bedrock areas, and in subsequent discussion of regional variations in tills and of drumlin formation, it will be suggested that such fabrics may belong to the end of a very long period of deposition, at which time deposition was at its most rapid. Three distinct stages in deposition are suggested. The first stage is the longest and involves the gradual accretion of till in favoured localities, dominantly on the Carboniferous bedrock areas or towards the centre of the basin but not wholly so. These favoured areas would initially be topographic hollows on the glacier bed both on a local and a regional scale. The second phase, involving the main period of drumlin formation and building, is suggested as being associated with the beginnings of ice decay, slowing and thinning. Increased rates of sedimentation and more widespread deposition would characterise this phase, again with local variations dependant upon a number of controlling factors such as bed topography, bed permeability, debris load and ice thickness. These are discussed below. The third phase represents final ice stagnation and the deposition of melt-out debris. The tills derived from this phase are probably localised to varying degrees and associated with former debris-rich areas within the ice.

The actual mechanics of till deposition are not yet fully understood. A major problem lies in the great number of variables involved, such as variables within the ice itself, in the particles of the debris load and in the glacier bed (Boulton, 1975; Sugden and John, 1975). Only recently has the problem been approached in the same theoretical detail, especially by Boulton (1975). His Critical Lodgement Index is an attempt at a simple analysis that might be applied to observed situations today in order to examine the role of certain variables in different situations, as well as to the deposits of former glaciers. (When the Critical Lodgement Index is equal to, or greater than, $\frac{N}{V_1 m}$ lodgement will occur, where N is the effective normal pressure of ice against its bed, V_1 is the glacier slip velocity and m is a constant.) This symbolises part of a general need in glacier mechanics to correlate the empirical and the theoretical approaches. Situations are more difficult to observe in larger ice sheets but at least some of the nature of the variability of sedimentation can be predicted given information on factors such as the hydraulic transmissibility of the bed, the shape of the bed and the composition of debris in transit.

In terms of the two depositional phases associated with moving ice described above, it is suggested that the temperature gradients in the basal ice as influenced by the shape of the bed would firstly initiate deposition in certain favoured localities. Current observations of bedrock/temperature gradients suggest that lodgement initially works towards a more even bed and is thus most prominent in topographic hollows (Nobles and Weertman, 1971), thus supporting the idea of a period of till accumulation producing deep tills over these hollows. Boulton's work has also suggested that, once initiated, this process of deposition tends to favour lodgement on a till bed rather than on a rock bed, the differing frictions of the bed materials, being important. This may be significant in drumlin formation.

Rates of Lodgement. As the factors controlling the process of lodgement itself are liable to combine in various ways, so the rates of till accumulation appear highly variable. More information is available today on the more easily examined valley glaciers than on the larger ice sheets. Under specialised conditions (e.g. post-surge) deposition of several metres of till a year is possible. Flint (1971) estimated 30 m in ten years on the Selfstrom glacier in Spitzbergen. Mickelson (1971) on the other hand estimated basal melt-out averaging as little as 5 mm and 28 mm a year on the Burrough's glacier in Alaska. Boulton estimated similarly small amounts for certain Svalbard glaciers but Goldthwait (1971) suggested that at the close of the Pleistocene ice sheets 200 mm per annum might be expected, while Sugden and John (1975) stated that "where the squeezing process is involved, localised sedimentation rates of several metres per year may be commonplace." Robin (1955) calculated that geothermal heat flux alone, in stagnant ice, might account for c.20 mm per annum, with moving ice contributing a further 20-40 mm from frictional heat, thus giving rates of around 6 m in a century. This would of course be subject to local variation dependent upon topographically induced stresses and ice thickness. It is difficult to relate such estimates to the Tweed ice-sheet but, in general terms, deposition is initially seen as slower and more localised but increasing and becoming more widespread with ice slowing and thinning. Local variations and potential explanations are discussed below. In the final (third phase), involving melt-out, all that can be deduced is that melt-out was sufficiently slow to allow fabric maintenance of overlying tills and therefore the removal of meltwater without the widespread creation of flowtill or injection features.
The efficiency of the sub-surface fluvioglacial systems in this process, and the probably high hydraulic transmissibility of the bed, particularly

on the sandstone-based areas, suggest that in relative terms, this deposition could have been fairly rapid.

REGIONAL VARIATIONS IN THE PATTERN OF DEPOSITION

Regional variations were noted in a number of aspects of the tills Colour changed markedly throughout the study area and particularly related to geological change. Colour was a ready indicator of thinner tills on the Old Red Sandstone and basalt areas in particular but proved more homogeneous and less valuable diagnostically on the deeper tills in any of the geological areas.

Variations in stone content were noted throughout the study area and although in some cases apparent variations were explicable in terms of changing lithology, others were less clear. The boulder content of the tills (over 30 cm in length) was also variable and although almost totally related to the occurrence of basalt bedrock, appeared to suggest concentrations particularly related to drumlin form. This is discussed below.

Particle size analysis also showed marked regional variations, the results of which interpreted in the light of the erratics content of the tills, the depth of till and the lithology of the local bedrock made significant contributions to the understanding of the derivation of the till matrix. Contrasts between the Carboniferous and Old Red Sandstone regions were particularly revealing, despite similar lithology and similar weak strata. In the Old Red Sandstone area particularly in the thinner tills along the pipeline section, the local rocks were the dominant constituents of the fine fraction especially where tills were less than 2 m in depth and towards the east of the area.

Sand percentages were particularly high with fine-sand fractions exceeding 50% even where counts of Old Red Sandstone erratics were low.

In the Carboniferous area however it is suggested that the influence of the local rocks is considerably less and a low representation in erratics content is only partially explicable in terms of rapid comminution but more particularly is a result of the lack of influence of local rocks at this level in the till. The increased silt percentages in this area dominantly reflect Silurian influence while the clay percentages, at a maximum towards the west, reflect in part a greater basalt influence. The matrix of the tills on the Carboniferous area appears to confirm the more exotic origins suggested by the evidence of erratics. It is therefore supports the idea of a prolonged period of accretion in these areas of deeper tills with a gradual masking of the local rock and its effects, the latter only becoming apparent where elevated positions produced more erosive basal activity and a longer period of contact between rock and active ice.

In terms of ice movement, the thinner tills on the basalt area reflect the influence of the local bedrock very quickly in the fine fraction, with a rapid rise in both silt and clay and a consequent fall in the sand fraction. This suggests therefore a very quick adjustment of the till matrix to changing geology wherever the glacier sole continues to engage parent rock actively, but a marked decline in local influences as tills thicken and gradual accretion produces tills of increasingly exotic origin.

<u>Till depth</u> varies considerably over the study area with marked variations both within and between geological areas. The consistently deep tills lie on the Carboniferous area with the shallowest tills on the higher basalt areas. The Old Red Sandstone areas show a variety of till depths although in the area examined in detail along the pipeline section, a greater tendency to shallower tills was noted than in the Carboniferous

area. Reasons for such variations are considered more fully once the evidence of erratics has been summarised.

Erratics: the regional pattern

The regional variations in the erratics content of the tills are esentially explicable in terms of two major variables; firstly in the changing local geology (particularly as it affects the thinner tills), and secondly in the depths of till overlying bedrock (and the degree to which materials at higher levels in the depositional sequence are therefore exotically derived). Within this simple framework, however, are a number of important variables, particularly the susceptibility of different rock types to comminution during englacial or sub-glacial movement. It is not possible therefore to make general statements as to whether or not a till matrix and its erratics content can be called local. Rather, tills in specific locations may be discussed or alternatively more general statements made that take into account relevant variables such as till depth, local lithology and topography.

There are essentially three main series of counts that contibute to this consideration of regional erratics patterns. Firstly, there are the 49 samples of the so-called "basal series" (Chapter 3), secondly the surface samples taken above this basal series (Chapter 4), and thirdly the "wide-area" (F) series stone counts which are surface samples taken from the middle Tweed and lower Teviot basins (Chapter 6). Although surface counts would be expected to differ from deeper counts, these differences have been examined and iterpreted in the light of the trench-based studies and their significance will be discussed fully in the consideration of vertical variations in tills.

Tills on the Old Red Sandstone area present a varying pattern of dominance either by local Old Red Sandstone fragments or the more exotic

Silurian erratics, the variation being primarily dependent upon the depth of till overlying local rock and to a lesser degree upon the location within the Old Red Sandstone region. Deeper tills, in their colour as well as thir erratics content, show increased Silurian influence towards the ground surface. In the east of the study area where increased Old Red Sandstone counts might have been expected at these higher levels, considerable break down of Old Red erratics in transit is suggested by their inability to survive in any appreciable concentrations away from local bedrock, even in areas where till colour, particle-size analysis and heavy mineral analysis suggest considerable influence in the till matrix.

Down-glacier onto the basalt area, till are often very thin, particularly on the higher more exposed areas, and concentrations of angular basalts can be considerable. In the few localities in these areas where deeper tills have been found it is the Silurian erratics that dominate and not the weak Old Red Sandstone fragments. This Silurian influence is particularly marked in deeper tills towards the centre of the basin where a tongue of Silurian-dominated debris masks local influence and suggests a more powerful ice movement, an interpretation also suggested by the greater elongation of drumlins in this area (Chapter 8).

Tills overlying the Carboniferous bedrock area have potentially the most varied sources, being farthest down-ice, and yet the dominant pattern is one of increasing influence of the far-travelled Silurian erratics. These become increasingly dominant down-ice, reaching 78% by numbers and 86% by weight in samples of the basal series. Surface percentages were even greater. These Silurian fragments were commonly over 12 cm in diameter, highly rounded, and averaged from 50-75 gms in samples over the Carboniferous area. In only a few samples, generally on exposed positions very close to bedrock, were local erratics relatively important (maximum 30%) but for the most part in the deep tills of the area Carboniferous erratics counts were very low, often being zero in surface samples, and particle size and heavy mineral analyses suggested Carboniferous influence in general to be very limited.

Of the other major erratics groups, the basalts declined generally eastwards over the Carboniferous area, achieving their maximum concentrations towards the north in the lee of the main basalt body where the lavas achieve a greater east/west extent, and where there may have been a more pronounced blocking effect on competitors in the more slowly moving ice (c.f. Gillberg, 1965, 1967).

In the other sedimentary group, the Old Red Sandstone, extreme susceptibility to attrition during transport ensures limited survival eastwards into the Carboniferous area, although it is likely that it is the Old Red Sandstone fines that are reflected in heavy mineral and particle size analyses results for the "surface" tills of the Carboniferous area rather than the local sediments.

A comparison of percentage weight with percentage numbers further depresses the apparent contribution of the sedimentary erratic groups except where very close to bedrock, (where erratics concentrations of 90% or more might be expected). Silurian erratics on the other hand show a very slight dominance of % weight over % numbers and although small, this does reflect the consistently sizable Silurian fragments encountered. Basalt weight percentages are very dominant upon initial incorporation into the till but move closer to parity (in % numbers) with increasing distance down-glacier.

In an area of easily eroded sedimentary strata it is this increasing dominance of Silurian erratics that is the most significant factor however. Apart from this, there is the related point of the great depths of till overlying Carboniferous bedrock to be explained. It has been suggested that lodgement must have gone on over a long period of time in such areas. If large quantities of debris were in transit in the ice at any time then it might seem resonable to expect evidence of this on the basalt and Old Red Sandstone bedrock areas, where ice stagnation would have left such debris. This is not necessarily so however. The time of actual stagnation would have been preceded by a period of decreasing erosional activity and increased depositional activity, particularly on the Carboniferous area. This would have had the effect of relatively decreasing the debris load in up-glacier areas compared to the Carboniferous area whose debris load might be considered as derived from a previous, more active glacial phase. It is also suggested that ice streaming tended to concentrate debris assemblages in the Carboniferous area: the amounts of melt-out tills at certain localities co-incident with these debris-rich zones in the Carboniferous area may thus misleadingly suggest greater quantities of englacial debris to be expected over areas of different bedrock, up-ice of the Carboniferous. Results from surface samples in both Old Red Sandstone and Carboniferous areas are in accord with the idea that Silurian-dominated debris was let down from within the ice around the period of final stagnation, but the variable till depths below this upper 1 to 2 m suggest the extent of depositional activity within the two areas to have been influenced by other factors.

Locally it has been shown that topographic variations may induce or prevent deposition (Boulton, 1975; Noble and Weertman, 1971), and topographic hollows in both Old Red Sandstone and Carboniferous areas appear to have developed deeper tills partly because of this modification of dynamic conditions at the glacier sole through the changing attitude of the bed. Other authors (Gillberg, 1965; Shilts, 1975) have shown how even quite small topographic prominences can block or deflect the

the pattern of erratics as moved by the basal ice. It seems that in the Tweed area, however, further explanation is needed. The most difficult factor to evaluate is the apparent change that took place in the character of the ice, particularly in the ice conditions at the glacier sole, somewhere between the Silurian and the Carboniferous bedrock areas. The explanation of this change may not be readily available in the evidence remaining today but certain potentially contributory factors can be suggested.

Given an initiation of lodgement within the Carboniferous area due to the achievement of certain critical conditions at the glacier sole, such a process would be self-encouraging in that lodgement indices are higher against a till bed than against a rock bed (Boulton, 1975). Boulton has also indicated that comminution during transport will produce a debris assemblage that is progressively more easily lodged, and that tills from sedimentary assemblages are the most easily lodged. A final factor may involve the hydraulic transmissibility of the glacier bed. Strata of low transmissibility tend to act as dams to water flow and thus increase the water pressure in all beds immediately up-glacier The marginal basalt areas may fulfil such a role within the Tweed basin with increased lodgement to be expected in zones occurring down-glacier, (in this case in the Carboniferous area). Upstream zones from these beds of low transmissibility tend towards erosion unless they themselves have a very high transmissibility. The Old Red Sandstone area would tend to have this high transmissibility and thus locally within this area conditions favourable to lodgement could have been created over a longer period.

<u>Counts of a finer size-fraction</u>

As a further contribution to the understanding of erratics patterns, counts were made of erratics in the size-range of 100-160 mm using a hand lens or simple binocular microscope. The results appear to conform to expected patterns, especially to trends suggested by the work of Dreimanis and Vagners (1971). In counts of Old Red Sandstone, basalt and Carboniferous erratics made close to bedrock, local bedrock dominates, especially when expressed as % weight. This equates with the first peak in the bimodal frequency polygon of Dreimanis and Vagners, namely an initial concentration in the coarser grades. Down-glacier the pattern becomes less clear and differences become less marked. In the Old Red Sandstone area as comminution proceeds there is a phase of dominance by this finer size-fraction before counts of both coarse and fine erratics become very low. Differences are also small within the Silurian group but the slight dominance of the finer erratics (100-160 mm; Chapter 5) over stones in the Old Red Sandstone area changes to a very slight dominance of the larger size-group on the Carboniferous area.

Heavy Mineral Analysis

The major use of heavy mineral analysis in the literature appears to have been in distinguishing different tills and the technique has generally been used in conjunction with other analytical techniques, with varying degrees of success (e.g. Arneman and Wright, 1959; Dreimanis and Reavely, 1953). The technique was used in a different manner in the present study however, in that, along with particle size analysis, it was used to examine the matrix of a single till sheet, especially in relation to bedrock change (Chapter 7). Some measure of success is claimed but results would be more difficult to interpret without the great weight of erratics evidence with which to make correlations. In particular it was hoped that this study would provide evidence relating to the softer sedimentary strata, so poorly represented in erratics counts. A major question lay in whether this softer material had been quickly reduced to its terminal grade by rapid destruction during transport or whether it had not, in any quantity, even reached the englacial levels represented by this Silurian-dominated debris. A major difficulty was the lack of available literature on the petrology of the relevant areas and it was not possible, for example, to concentrate on any particular trace element or mineral as being characteristic of any particular rock grouping.

The most successful application of the technique was in relation to the occurrence of basaltic elements in the heavy mineral grades. Minerals such as apatite, horneblende and the pyroxenes, particularly augite, clearly indicated the influence of igneous rocks in the fine grades and were therefore reliable indicators of basalt influence at this level. For the most part they mirrored the rapid rise in basalt erratics over basalt bedrock areas and their subsequent decline over the Carboniferous area, although consistent horneblende percentages perhaps suggest a greater survival in these finer grades. Significantly the erratics peak on the basalt bedrock area occurred slightly up-ice of the peak of basalt influence in this heavy mineral size-fraction.

Although other changes took place regionally in the concentrations of many of the other heavy minerals, those results could be less specifically interpreted since a number of minerals potentially had origins in more than one geological grouping. In particular the tills on the Carboniferous area, illustrated a great range of heavy minerals indicating the potentially varied origins of this material. Potential Silurian influences were identified, particularly in certain garnets (Chapter 7), but the question of Carboniferous influence was less satisfactorily resolved, although it appears to be slight. The evidence of the micas, an exceedingly slight biotite dominance on the Old Red Sandstone area, and a general biotite dominance over the basalts, gradually giving way to a muscovite dominance into the Carboniferous area, could be interpreted as supporting some Carboniferous contribution (Ragg et al., 1960) but the differences are small in most instances. The evidence of the other sedimentary minerals is ambiguous because of the apparent similarity of Old Red Sandstone and Carboniferous mineral assemblages (Ragg et al. 1961).

Although there did seem to be a degree of correlation between Silurian erratics percentages and concentrations of Fe minerals, this could not be satisfactorily explained. The limited evidence in the literature does not suggest such a correlation and some of the explantion may lie in problems of identification due to heavy staining of these far travelled minerals. Despite such identification and derivation problems however, "typical" tills could be identified within each area with patterns of change detectable across bedrock areas in the direction of ice movement (Chapter 7), and tills within any bedrock area could be interpreted in the light of these models.

LOCAL AND VERTICAL VARIATIONS IN TILL COMPOSITION

Attention was already been drawn in this summary to the idea of till zonation, the ideal pattern comprising an upper till dominated by exotic Silurian erratics, an underlying zone of more mixed till with considerable variations in composition depending upon depth of till, and finally a till of almost 100% local bedrock in both coarse and fine constituents, the so-called "intermediate till-zone" (Chapter 2). The surface Silurian-dominated zone is seen as being derived from debris bands at one time high in the basal ice and may in some instances be partly melt-out till. Below this, the zone of mixed till would be similarly Silurian dominated with this dominance being stronger where till is deeper. The basal till zone, the "intermediate till zone" is represented in few sections in the Carboniferous area but is seen more frequently within the basalt and Old Red Sandstone areas. This zone represents the period when local bedrock was being actively eroded and incorporated into basal ice. The lack of foreign erratics suggests that perhaps this zone approximates to the traction zone of the ice at its most active phase. In the more exposed areas of Old Red Sandstone bedrock this "intermediate till zone" may be as thick as the overlying Silurian-dominated material. This overlying debris would have been largely transported across the Old Red Sandstone area but for the ice sheet having begun to decay, thus causing widespread deposition as the ice thinned, some of this deposition occurring after stagnation. Reasons for the variable extent of the "intermediate till zone" were offerred in Chapter 2. Erratics counts made in tills of the basal series and compared with counts made in surface tills in the same areas, show changes in composition that reflect these different zones. Least change occurrs within sections where underlying tills are deeper and most change where tills are thin enough to expose bedrock or the intermediate till zone within the section. The decline in local erratics vertically can be considerable, up to 80% over a 2m depth having been recorded in the Old Red Sandstone area.

The general pattern is of dominance by local erratics within this variable intermediate till zone at depths of 1m-1.5m above bedrock. The depth of this zone may vary considerably (Chapter 2). In many sections, particularly on the Carboniferous area, this part of the sequence is not visible but is deeply buried and a more homogeneous pattern occurrs within the vertical extent of the section. Even here however the Silurian erratics exhibit a marked rise towards the surface of the section.

Part of the vertical decrease of sedimentary erratics may be due to the inability of the weak sediments to survive glacial transport. This is seen in some parts of the Old Red Sandstone area in particular where particle size and heavy mineral analyses suggest the presence of Old Red materials in the matrix. The more resistant basalts do reach 70% in surface counts but in areas of much thinner tills.

Much of this vertical decline, however, is seen as being due to the different origins of the higher materials in the section, with the surface samples having been derived from levels once high in the basal ice and thus being most exotic in origin and having limited local contamination.

Although the Old Red Sandstone area has several sites with these pronounced vertical changes in composition it is not possible or realistic to quote figures for average change with vertical distance from bedrock Too many variables influence this (Chapter 4). In general terms it is possible to recognise a very rapid initial decline in local rock concentrations above the intermediate till zone, this vertical change becoming less marked towards the ground surface in deeper tills. This is especially true towards the east of the Old Red Sandstone area where it is suggested that shearing carried some surviving Old Red Sandstone erratics to higher levels in the basal ice.

Particle size analyses were also carried out on surface tills and related tills of the basal series. Although potential alteration of tills during melt-out is recognised, the underlying trends noted in this study relate closely to the erratics evidence and melt-out interference often appears minimal. Tills of Silurian dominance in particular appear to produce higher silt % and in general there is an increase in silt concentrations towards the surface. This is not necessarily at the expense of the clay fraction, however, which may have been expected to suffer most from any squeeze-melt. In a site close to bedrock on the Carboniferous area for example the clay % rose dramatically by 28% between the locally dominated basal till (72% sand) and the basalt and Silurian dominated surface areas. Thickness of till above bedrock is again recognised as a major influence upon the degree of change noted within any section, greatest change again being evidenced where bedrock or the intermediate till zone appeared in the section. In the Old Red Sandstone area this generally involves a change from sand-dominated lower tills to the characteristically silt-dominated tills at higher levels. On the basalt area high clay percentages characterise the basal till on bedrock while the upper tills can show a high sand fraction as well as the expected silts, indicating a degree of carry-over of Old Red Sandstone influence at least in the matrix. Such results when applied to erratics and heavy mineral evidence clearly show the compositional changes associated with this vertical zonation, representative of differing origins both geologically and in relation to position within the active ice sheet and its bed immediately prior to cessation of movement. The zoning envisaged could have been accomplished with or without a melt-out phase although it is suggested that previously presented evidence locally confirms the existence of such a phase.

DRUMLIN FORMATION

Although the primary aim of this thesis was not an examination of drumlin formation, it is suggested that the till studies undertaken here have some contribution to make to a better understanding of drumlins and their formation. Recent work (Rose and Letzer, 1975; Doornkamp and King 1971) has highlighted the great variety of measurements that may be made in studies of drumlins, but it was not within the scope of this thesis to undertake such measurements. Instead the evidence considered here involves three aspects: fabric analysis, erratics evidence, and visual evidence (from the trench section and surface morphology).

The orientations of the Tweed drumlins must be taken to reflect the directions of regional ice movement at some relatively late stage of this last glaciation. Although Trenhaile (1975) suggested that drumlins were commonly formed close to end moraines, Sugden and John (1975) believe that more normally drumlins were produced at some distance from the ice margin where glaciological conditions favoured streamlining. The main drumlin belt is envisaged by the two latter as being preceeded by a zone of drumlinised ridges, a situation strongly resembling that of the Tweed area.

Boulton (1972), however, illustrated the difficulty of dividing an ice mass into zones of erosion and deposition reflecting a gradually changing emphasis between source and ice margin. Factors such as the bed morphology, the water transmissibility of the bed and the thickness of the ice all affect basal pressure conditions locally and thus erosion or deposition. The influence of these or other factors is illustrated for example, in the range of elongation of the Tweed drumlins (Chapter 8), in this case probably indicating variable ice velocity or even debris load. Drumlin morphology also varies in other respects. Superimposition of drumlins occurrs in some areas, again perhaps indicative of changes in till supply during formation.

It is suggested that the initiation of till deposition and of drumlin formation are not the same problem and are not really contemporaneous. Drumlin formation is most probably a fairly late stage in the depositional pattern. Possible reasons for regional variations in till deposition have been presented previously and accepting a prolonged period of deposition, it is perhaps necessary to examine other factors that might have contributed to the initiation of the bulk of actual drumlin formation.

Fabric Analysis. The till fabrics examined here are considered to belong to a fairly late phase in drumlin formation, and clearly indicate a streamlined pattern of flow related to the movement of debris over and around an already established streamlined form. Some of the tills examined may even have undergone final modification by gradual squeeze-melt but this did not destroy the fabric's clear relationship to drumlin form. The bulk of the fabric is considered to be essentially a product of englacial activity with minimal adjustment during deposition, most probably confined within the parallel plane. (The crucial fabrics examined in the stoss-end of the Hardacres drumlin (Chapter 8) are considered to represent compact lodgement till and not melt-out till.)

The apparent discrepancy between the author's results and those of Wright (1957) in the Wadena field, and Andrews and King (1968) in a Yorkshire site may be partially attributable to the differing sampling positions within the drumlins. It is also perhaps false to assume that the features examined in each instance had a common origin. Within the author's study area there is a need to examine a greater number of sites, at a variety of depths and more widely distributed on the drumlin form to include high and low, stoss and tail sites.

The Tweed fabrics appear to have an affinity with recent work by Gravenor (1974) in the Yarmouth drumlin field, Nova Scotia. At depths similar to those of the Tweed fabrics (down to 3m) Gravenor found well developed fabrics in which stoss end samples clearly showed the divergent flow around the drumlin form. Deeper fabrics showed much less clear definition. Evenson (1971) in an examination of drumlin fabrics, found similar plunge angles to the Tweed fabrics, a similar development of a transverse peak and a close approximation of fabrics to regional drumlin orientation. Evenson's ideas of drumlin formation through the transport of till towards the drumlin crests as a flow from high to low pressure areas at the glacier sole, do not appear to be supported by the Tweed fabrics results however.

If the Tweed drumlin fabrics thus represent ice flow around a drumlin then the evidence for the genesis of the drumlin must be found much deeper in the sections examined or alternatively at the base of active ice sheets today. Given the practical difficulties of detailed examination of either situation it is necessary to revert to such evidence as is available in the present context.

The idea of some form of obstruction being involved in drumlin inception has been frequently examined in the literature (e.g. Gravenor 1953; Kupsch 1955; Lemke 1958) and the author considers this to have a particular relevance to the Tweed drumlin field. It is suggested that there is considerable cumulative evidence to support the idea of some form of obstruction being involved in many of the Tweed drumlins. This may be summarised as follows.

(i) The fabric patterns clearly indicate ice flow around some pre-established form.

(ii) Many drumlins have irregular and often steep stoss ends (suggestive of some resistance to ice flow) and which in themselves are imperfectly streamlined.

(iii) Erosional depressions lie around the stoss ends of some drumlins in a form more commonly associated with crag-type obstructions.

(iv) Geological evidence indicates a large number of often small igneous bodies, particularly in the Old Red Sandstone area, and crag-and-tail and drumlin forms were apparently established around these resistant bodies.

(v) Erratics evidence in drumlins at Todrig (NT 791421, Chapter 6) and Yarlside (NT 617383, Chapter 9) suggested resistant rock cores incorporated within drumlins whose appearance is similar to normal till drumlins.

In the Black Hill study (Chapter 9) erratics evidence indicated a trachyte core in a drumlin ridge formed down-ice of the flank of Black Hill.

(vi) Clapperton (1968) noted that a few of the drumlins east of Kelso, in the centre of the basin were composed at least partly of water-worn deposits, suggestive of ice moving over earlier fluvioglacial deposits.

In the light of Boulton's (1972, 1975) recent theories and observations on till lodgement and drumlin formation, it may be that we should look beyond the stoss ends of drumlins for evidence of obstructions around which these features may have formed. Boulton observed for example the accumulation of till on the up-glacier slope of a roche moutonnee.

It has been suggested previously that lodgement may have gone on for some considerable period under the active maximum ice sheet with local variations induced by the variability of the glacier bed and the impact of this and other less discernible variables of basal ice temperatures and pressures. As the debris-charged ice began to slow however, Boulton's (1975) critical lodgement index would be achieved more widely across the glacier sole and net basal melt would gradually lower the debris load towards the glacier bed. At this stage of increased lodgement the igneous bodies would conceivably control local patterns of deposition both through direct basal pressure changes associated with ice movement about themselves and the associated induced lodgement patterns but also, and most importantly within the Carboniferous area, in the production of debris-rich streams in the basal ice. Gillberg (1967) recognised a very detailed mosaic of secondary deflections at the base of the ice sheet which seemed to follow terrain very closely and Boulton (1975) has observed how streaming produced debris-laden bands of 2 m thickness in the basal till.

There is evidence in the fabrics for deposition on the face of the drumlin by over-riding ice and of accretion on the flanks by ice flowing around the drumlin (Chapter 8), but it is suggested that within these debris-rich ice streams may be recognised the potential origins of other streamlined forms being "seeded" off the flanks of these larger controlling bodies. With particles moving at different speeds in the glacier sole (Boulton 1973) and with the ice continually slowing and thinning then obstructions may be expected to form within the basal ice-borne tills themselves. Boulton (1972) for example, indicated how debris-rich basal ice became very rigid and much less plastic. Smalley and Unwin (1968) recognised a fall in stress levels at the glacier sole producing a sudden change in basal tills from a state of dilatancy to a static stable mass on the glacier bed with no local stresses now capable of eroding it. (It is the explanation of this critical change in the dynamics of the basal ice, associated with slowing and thinning, that is so difficult to observe today and that remains a critical unknown variable in drumlin formation.

In the sections observed in the Tweed drumlin field, one particular boulder concentration was noted near the stoss end of the Hardacres drumlin but this was possibly too superficial and too far up-glacier to be equated with a blockage role. In general sections examined were too shallow to hope to identify such features. The poorly defined fabrics noted at depth in the heart of some drumlins by Gravenor (1974) may, imply a till core in many drumlins. It is also conceivable that at this time of increased lodgement the most favoured areas for deposition included areas of previous till deposition rather than rock areas (Boulton, 1975). J. Menzies (pers. commun.) has suggested that many drumlins in the Glasgow area appear to have developed over topographic hollows.

It is therefore suggested that the Tweed drumlins, in part at least, owe their origins and pattern to the occurrence within the basin, particularly in the up-glacier areas, of numerous resistant igneous bodies, which induced streaming and debris concentrations in the basal ice. In addition there may have been a major change in basal pressure conditions within the ice sheet causing a previous pattern of more localised lodgement to be replaced by a more widespread and more rapid deposition as the ice sheet began to slow and thin. During this thinning, obstructions would also form within the large masses of till locally concentrated within the basal ice, thus providing nuclei for drumlin formation as the ice became unable to move the debris-rich concentrations that developed. Areas of former deposition may have been significant in initiating this. Hill's (1973) work on drumlins in N. Ireland suggested that some periodicity in ice sheet characteristics had apparently induced zones of deposition resulting in bands of high drumlinsdensity lying normal to the direction of ice flow. Any such periodicity, if present in the Tweed ice sheet, could only have further contributed to the provision of till nuclei and debris streaming.

Scattered resistant igneous bodies acting as obstructions are not necessarily a pre-requisite of all drumlin formation in all drumlin fields but it is suggested that this played an important part within this particular field. Apart from the actual formation of features around these bodies and the implications of the streaming patterns as suggested above, it is not known to what extent the local shearing motions or other motions initiated in the basal ice due to its passage over and around the irregular glacier bed may also have contributed to patterns examined farther down-glacier.

It is this last major change in conditions in the basal ice that is most difficult to observe or quantify in any way other than in the general observation, evidence for which has been presented in this thesis, that a critical change in the mass balance of the ice sheet induced ultimate stagnation. When this change occurred the presence of rock obstructions on the glacier bed appears to have played a significant role both in the evolution of drumlins and in controlling the overall pattern of occurrence.

APPENDIX

Items excluded from the Appendix

Since results of counts in the main erratics groups associated with the Todrig drumlin study (Chapter 6) and the Black Hill trachyte study (Chapter 9) have already been fully illustrated within the thesis, these results are not tabled here. (Fig. 45a illustrates the 19 sites associated with the Todrig drumlin study while Figs. 57 to 61 fully illustrate results from 146 sites in the Black Hill study.)

Field data concerning orientation analyses are not included. Fabric diagrams clearly show the patterns depicted by these data and a comprehensive analysis is also provided in Figs. 48 to 56b inclusive.

APPENDIX A.

RESULTS OF STONE-COUNTS OF THE BASAL SERIES (CHAPTER 3)

Results are shown for % number and % weight only. (Percentage volume was measured in some instances but varied only marginally from that of % weight.)

Part 1 Locations of samples of the basal series. 6-figure map references are given. All references should be prefixed NT.

S.1	858413	S.18	769419	S.35	703428
S.2	854414	S.19	(destroyed)	S.36	700428
S.3	850414	S.20	763418	S.37	692428
S.4	846415	S.21	762418	S.38	689428
S.5	842417	S.22B	758418	S.39	688428
S.6	838419	S.23	755418	S.40	685429
S.7	832422	S.24	751418	S.41	678430
S.8	824423	S.25	747418	S.42	675432
S.9	818424	S.26	742418	S.43C	672433
S.10	811424	S.27	739418	S.X	643445
S.11	806423	S.28	735419	S.G.1	638446
S.12	801423	S.29	732420	S.G.2	637446
S.13	796422	S.30	728422	S.G.3	634445
S.14	789421	S.31	724423	S.G.4	630445
S.15	782420	S.32	719424	S.G.5	627445
S.16	778419	S.33	716426	S.G.6A	623446
S.17	772419	S.34	713427		

Part 2 COMPOSITION (overleaf)

For any single erratics group, the top line indicates % weight.
The bottom line indicates % numbers.

SAMPLE NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	20
NO. OF STONES	87	94	91	98	64	94	62	99	87	74	63	80	56	82	78	78	108	77	38
TOTAL WEIGHT (gms)	3995	5370	6258	5706	3816	3753	3841	4790	5378	3217	3551	3862	2300	4400	2766	3990	2593	2015	538

(Percentages are expressed to the nearest whole number.)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	20
% SILURIAN	76	78	63	76	66	81	77	81	58	84	80	70	86	69	49	80	81	62	55
	71	70	66	65	64	72	63	78	70	69	65	64	64	56	53	64	68	71	58
% BASALT	2	11	18	15	9	12	17	6	11	6	10	5	8	6	44	8	5	14	15
	8	7	12	15	8	13	16	6	9	8	14	14	9	12	22	15	8	14	13
% OLD RED SANDSTONE	-	-	1	-	9	1	-	-	14	-	-	3	1	-	-	-	1	-	1
	-	-	1	-	2	2	-	-	1	3	-	1	2	-	-	-	2	-	3
% CARBONIFEROUS	13	6	11	2	10	1	2	6	7	3	7	7	4	22	7	10	5	4	7
	9	11	7	4	15	2	8	4	9	10	10	10	11	22	15	14	10	8	8
% TRACHYTE-FELSITE	2	-	-	1	-	-	-	2	2	-	-	-	1	-	1	-	-	-	2
	1	2	1	2	2	1	-	1	2	-	-	1	2	-	1	1	-	1	5
% QUARTZ, CHALCEDONY	3	3	3	3	3	2	1	2	6	-	2	13	3	1	2	-	4	2	11
	2	5	6	4	6	3	3	4	3	3	3	5	5	4	4	-	5	1	5
% VOLCANIC AGGLOMERATE	1	1	-	3	-	-	1	-	-	-	-	-	-	2	-	-	1	-	-
	1	1	1	2	2	1	3	1	-	-	2	-	-	1	-	-	1	-	-
% CHEVIOT ANDESITE	-	-	-	1	-	1	-	-	1	1	-	-	-	-	2	-	-	-	-
	1	-	1	2	-	2	2	-	1	1	-	-	-	-	1	-	1	-	-
% OTHERS	5	1	3	1	3	3	1	3	1	5	1	1	5	1	1	2	4	18	8
	6	4	4	5	3	3	5	6	3	7	4	5	7	5	4	5	6	5	8

SAMPLE NUMBER	21	22B	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
NO. OF STONES	64	82	72	64	75	80	80	86	84	88	86	82	70	142	64	81	71
TOTAL WEIGHT (gms)	2762	2673	2961	5214	3658	3338	4016	3390	4496	4158	5806	4711	5476	5218	3719	8939	2215

(Percentages are expressed to the nearest whole number.)

	21	22B	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
% SILURIAN	81 56	46 61	70 67	67 48	85 51	27 33	13 24	35 34	32 31	22 24	20 22	12 21	- 3	16 18	15 25	44 36	32 44
% BASALT	15 20	38 20	23 20	25 25	12 32	71 55	63 35	56 52	63 55	48 44	72 54	85 59	99 88	80 75	43 14	33 14	42 9
% OLD RED SANDSTONE	- -	1 1	- 3	- -	- -	1 4	- 3	1 4	1 2	27 16	2 4	3 18	- -	1 3	35 53	18 35	21 31
% CARBONIFEROUS	1 11	7 7	4 6	9 25	3 9	1 5	21 30	3 5	1 6	- 1	- -	- -	- -	- -	- -	- -	- -
% TRACHYTE-FELSITE	- -	- -	- -	- 2	- -	- -	1 1	1 1	- -	1 5	3 6	- 2	- -	- -	5 2	4 7	3 6
% QUARTZ, CHALCEDONY	- 3	- 1	1 4	- -	- 3	- 1	- 3	- -	1 4	2 5	2 4	- -	1 4	- 1	- -	- 3	- -
% VOLCANIC AGGLOMERATE	1 3	2 4	- -	- -	- -	- -	- -	1 2	- -	- -	1 2	- -	- -	1 1	- -	3 1	1 3
% CHEVIOT ANDESITE	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -
% OTHERS	1 6	7 6	1 2	- 2	1 5	1 3	2 5	4 4	2 2	1 6	2 7	- -	1 4	3 2	2 6	- 5	2 8

SAMPLE NUMBER	38	39	40	41	42	430	X	G.1	G.2	G.3	G.4	G.5	G.6.A
NO. OF STONES	62	90	119	75	104	100+	100	63	99	73	106	82	85
TOTAL WEIGHT (gms)	1953	4319	7322	6918	4290	-	3897	3696	5235	3124	3441	3062	2095

(Percentages are expressed to the nearest whole number.)

% SILURIAN	28 40	59 34	43 37	3 17	9 20	- -	80 68	1 8	53 26	43 32	57 47	59 56	4 6
% BASALT	39 5	3 10	23 9	85 33	16 11	- -	1 2	1 2	5 4	43 15	7 7	16 12	- -
% OLD RED SANDSTONE	2 40	14 28	31 41	7 36	62 65	100 100	15 22	98 89	40 62	14 48	28 40	16 26	96 94
% CARBONIFEROUS	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -
% TRACHYTE-FELSITE	26 6	11 8	3 8	4 4	- 1	- -	- -	- -	1 2	- -	- -	6 1	- -
% QUARTZ, CHALCEDONY	- 2	2 2	- -	- 1	- -	- -	- 2	- -	- -	- 1	- 1	- -	- -
% VOLCANIC AGGLOMERATE	1 2	9 11	- 1	1 3	12 3	- -	1 2	- 2	1 2	- -	6 3	1 1	- -
% CHEVIOT ANDESITE	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -
% OTHERS	5 5	2 7	1 4	- 5	- -	- -	2 4	- -	1 4	1 4	1 3	3 4	- -

APPENDIX B.

OTHER STONE-COUNTS FROM WITHIN THE TRENCH SECTION (CHAPTER 4)

Many sites yielded too few stones to produce meaningful results. These have not been considered in previous discussions. The locations, depth etc. of those used in the text can be gained from the relevant diagrams.

Results are expressed as % weight and % numbers as illustrated in appendix A.

(O. : sites of orientation studies)

SAMPLE NUMBER	Rd.X 5.A	Rd.X 5.B	W.B. 2	22A	24A	Rd.X 12.A	Rd.X 12.B	29A	29C	32X	32Y	32Z	35B	35C	37A	37B	39A	43A	43B	G.6.	O.14	O.15	O.17	O.18	O.19	S.A.
NUMBER OF STONES	100	91	100	66	84	81	100	14	33	17	17	100	120	100	49	100	97	48	83	62	63	75	95	86	68	51
TOTAL WEIGHT (gms)	-	1507	4499	1567	1329	2988	-	1252	690	432	1706	-	4939	-	3826	-	6130	2150	2284	2897	4153	3122	5259	3491	1746	1506
% SILURIAN	-	60	23	72	61	20	-	14	12	42	62	-	26	-	86	-	22	58	60	79	7	16	37	4	11	66
	-	53	31	58	55	22	-	36	21	47	12	-	35	-	41	-	39	44	47	76	24	16	22	21	21	49
% BASALT	-	9	20	21	10	33	-	84	83	56	23	100	36	-	1	-	30	22	15	17	86	77	42	92	85	18
	-	10	15	30	14	37	-	50	64	47	77	100	30	-	12	-	31	23	17	15	52	66	63	67	66	24
% OLD RED SANDSTONE	-	1	-	1	2	11	-	1	4	2	15	-	28	100	5	100	26	13	22	3	1	1	-	-	1	-
	-	1	1	2	2	3	-	7	6	6	6	-	23	100	37	100	12	8	29	6	3	1	1	1	2	-
% CARBONIFEROUS	100	20	56	3	21	32	100	-	-	-	-	-	-	-	-	-	-	-	-	-	6	5	4	-	1	15
	100	24	48	2	17	30	100	-	-	-	-	-	-	-	-	-	-	-	-	-	16	9	5	4	6	18
% TRACHYTE-FELSITE	-	-	-	-	-	-	-	-	-	-	-	-	6	-	2	-	14	3	-	-	-	-	8	-	3	-
	-	-	-	-	-	1	-	-	-	-	-	-	3	-	4	-	5	8	1	-	-	-	1	-	2	-
% QUARTZ, CHALCEDONY	-	5	-	-	1	-	-	-	-	-	-	-	3	-	-	-	-	1	-	-	-	-	7	1	-	1
	-	3	1	-	2	1	-	-	-	-	-	-	3	-	-	-	2	2	-	-	-	1	2	1	-	2
% VOLCANIC AGGLOMERATE	-	1	1	1	1	-	-	-	-	-	-	-	1	-	5	-	3	2	1	-	-	-	1	-	1	-
	-	2	2	3	1	-	-	-	-	-	-	-	2	-	2	-	5	4	4	2	-	-	2	-	2	-
% CHEVIOT ANDESITE	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
% OTHERS	-	4	1	2	5	4	-	1	2	-	-	-	1	-	-	-	6	1	1	-	1	1	-	2	1	1
	-	7	4	6	8	6	-	7	6	-	6	-	3	-	4	-	5	10	2	2	6	5	3	4	2	8

APPENDIX C.

RESULTS OF SURFACE STONE-COUNTS

(RELATED TO SAMPLES OF THE BASAL SERIES, CHAPTER 4)

Sample numbers correspond to samples of the basal series and sample locations are given in Appendix A, part 1. Only sample 34B does not relate directly to a basal sample. This was taken mid-way between S.34 and S.35 to examine the very thin till on the highest point of the basalt ridge.

Within the text, all samples in this series were recognised by the prefix S.S.

All samples contained 100 stones and figures are thus expressed as percentages.

SAMPLE NUMBER	1	4	5	8	9	Rd.X 5	11	13	13A	13B	13C	14	15	16	18A	18B	18C	18D	21	24
SILURIAN	76	74	75	73	77	75	70	68	74	73	69	66	67	65	65	67	67	69	68	65
BASALT	8	10	9	9	7	11	15	18	13	15	16	17	19	15	17	20	19	19	21	22
OLD RED SANDSTONE	-	-	1?	-	-	-	1?	1	-	1?	-	1	1?	2	-	1	1	2	1	1
CARBONIFEROUS	2	4	2	4	2	1	2	1	2	3	2	4	2	3	1	4	1	3	1	2
VEIN ROCKS	7	3	3	5	4	3	4	5	5	4	4	5	4	5	5	1	5	3	3	5
VOLCANIC AGGLOMERAGE	2	1	2	1	-	-	1	-	2	-	1	1	1	2	2	2	1	-	-	-
CHEVIOT ANDESITE	-	-	2	-	-	1	-	-	-	-	-	-	-	-	-	1	-	-	-	-
TRACHYTE	-	1	-	-	1	2	1?	1	1	-	1	-	-	1	-	1	-	1	1	1
OTHERS	5	7	5	8	9	6	6	6	3	4	7	6	6	7	9	3	5	3	5	4

SAMPLE NUMBER	25	28	29	31	33	34	34B	35A	36A	37	38	39	41	42	43	G.1	G.4	G.5	G.6
SILURIAN	60	43	41	21	17	32	17	32	46	55	40	37	69	54	75	85	76	70	72
BASALT	32	47	53	68	70	56	70	42	20	20	22	35	10	25	13	3	13	17	11
OLD RED SANDSTONE	1	1	1	4	8	3	8	8	23	15	4	13	13	3	9	9	6	4	13
CARBONIFEROUS	2	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
VEIN ROCKS	-	3	-	2	1	3	-	1	-	1	2	1	1	1	3	1	1	2	2
VOLCANIC AGGLOMERATE	-	-	2	-	2	3	4	4	2	2	11	-	-	2	1	1	1	2	1
CHEVIOT ANDESITE	-	-	-	-	-	-	-	4	-	-	-	-	-	-	-	-	-	-	-
TRACYTE	-	1	1	2	1	2	-	2	5	3	13	3	2	5	-	-	-	-	-
OTHERS	2	4	3	3	1	1	4	8	5	4	6	6	5	5	5	1	3	5	1

APPENDIX D.

SOME EXAMPLES OF SURFACE BOULDER COUNTS (STONES OVER 30 cm LENGTH)

Two types of locations were examined; tips of boulders removed from agricultural land, or counts of suitably-sized fragments within drystone dykes.

100 boulders were counted at each location. Results are expressed as percentages.

GEOLOGICAL AREA *	O	O	O	O	B	B	B
MAP REFERENCE	626 447	619 406	623 406	625 404	725 429	727 428	728 428
TYPE OF SITE	Tip	Tip	Dyke	Dyke	Tip	Tip	Dyke
BASALT	67	68	80	40	90	85	92
SILURIAN	22	16	6	15	5	11	4
OLD RED SANDSTONE	10	11	6	42	2	2	-

GEOLOGICAL AREA *	B	B	O	O	O	O	O
MAP REFERENCE	727 426	726 425	693 429	694 429	695 429	683 398	683 398
TYPE OF SITE	Dyke	Dyke	Dyke	Dyke	Dyke	Dyke	Dyke
BASALT	88	98	70	88	68	80	72
SILURIAN	5	-	19	7	24	17	25
OLD RED SANDSTONE	4	-	5	1	1	1	2

All map references should be prefixed NT.

*
B : Basalt bedrock area.
O : Old Red Sandstone bedrock area.

APPENDIX D.

COUNTS OF PEBBLES IN THE SIZE RANGE 100-160 mm

(CHAPTER 5)

All samples belong to the basal series or intermediate levels in the trench.

Sample locations are indicated in Appendix A, part 1.

Figures show % concentrations of the major erratics groups.

SAMPLE NUMBERS	4	10	Rd.X 5.B	14	15	23	26	27	Rd.X 12A	28	31	32	33	37A	39
SILURIAN	66	53	41	48	60	54	19	30	29	29	20	16	11	18	35
BASALT	14	18	14	13	17	25	63	41	43	49	55	48	75	16	19
CARBONIFEROUS	1	17	25	24	10	11	4	16	11	5	-	-	-	-	-
OLD RED SANDSTONE	-	1?	2	1	2	3	1	5	1	6	13	22	4	52	25
VEIN ROCKS	5	3	5	1	3	1	1	2	4	3	4	-	3	-	3
AGGLOMERATE	4	-	-	-	-	-	-	-	-	-	2	-	-	1	4
TRACHYTE	-	-	1	-	-	-	1	-	1	-	2	6	1	3	5
CHEVIOT ANDESITE	2	-	-	1	-	-	-	-	-	1	-	-	-	-	-
OTHERS	8	8	11	10	8	7	6	6	11	7	7	8	5	10	9

SAMPLE NUMBERS	39A	40	42	43B	43A	G.1	G.2	G.3	G.5	G.6.A
SILURAIN	32	33	27	33	41	12	31	38	57	43
BASALT	30	28	11	24	23	-	7	18	16	35
CARBONIFEROUS	-	-	-	-	-	-	-	-	-	-
OLD RED SANDSTONE	26	19	53	23	14	88	50	30	18	14
VEIN ROCKS	-	1	2	-	2	-	1	1	1	-
AGGLOMERATE	-	5	-	-	5	-	1	3	1	-
TRACHYTE	3	4	1	4	6	-	-	-	-	-
CHEVIOT ANDESITE	-	-	-	-	-	-	-	-	-	-
OTHERS	9	10	6	11	9	-	10	11	7	8

APPENDIX E.

SURFACE STONE-COUNTS FROM THE "WIDE-AREA" SERIES (CHAPTER 6)

Certain counts from the trench-related (S.S.) series (Chapter 4) and the Black Hill study (Chapter 9, Figs. 57-61) were also incorporated into this series in the text.

The results of these samples are not repeated here.

Part 1 SAMPLE LOCATIONS.

Locations are given as six-figure map references. All references should be prefixed NT.

F1	692367	F16	693346	FA1	597287
F2	692390	F17	654359	FA2	587258
F3	695409	F18	724356	FA3	584244
F4	718406	F19	702323	FA4	610229
F5	722393	F20	657399	FA5	591212
F6	745435	F21	653380	FA6	652251
F7	764434	F22	658345	FA7	687271
F8	791430	F23	657320	FA8	693287
F9	810414	F24	620326	FA9	687302
F10	826429	F25	595322	FA10	614274
F11	785406	F26	599339	FA11	612248
F12	767401	F27	613355	FA12	648279
F13	789394	F28	589357	FA13	658305
F14	760380	F29	741402	FA14	618303
F15	727375				

Part 2 STONE-COUNT RESULTS (overleaf)

Results are expressed as % (to the nearest whole number)

SITE NO.	F1	F2	F3	F4	F5	F6	F7	F8
NO. OF STONES	115	137	107	110	111	101	109	112
SILURIAN	83	11	40	33	61	36	62	70
BASALT	10	88	48	61	33	58	28	17
OLD RED SANDSTONE	3	2	-	3	3	1	2	1
VEIN ROCK	3	-	1	2	3	-	2	5
AGGLOMERATE	1	-	2	1	-	2	4	3
TRACHYTE	-	-	9	-	-	3	1	1
CARBONIFEROUS	-	-	-	-	-	-	-	-
CHEVIOT ANDESITE	-	-	-	-	-	-	-	1
OTHERS	2	-	-	2	2	-	1	3

SITE NO.	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19	F20	F21	F22
NO. OF STONES	130	111	118	105	115	114	100	108	100	108	104	109	113	102
SILURIAN	78	80	77	81	75	76	69	69	23	75	47	64	52	91
BASALT	9	9	9	10	12	11	26	24	73	13	44	15	32	4
OLD RED SANDSTONE	-	-	1	1	1	1	2	4	1	5	5	8	5	2
VEIN ROCK	7	5	5	3	5	5	1	-	2	3	2	1	1	2
AGGLOMERATE	3	1	2	1	1	1	1	-	1	1	-	2	2	-
TRACHYTE	1	-	-	2	-	-	-	-	-	-	-	8	6	-
CARBONIFEROUS	-	1	1	-	-	2	-	-	-	-	-	-	-	-
CHEVIOT ANDESITE	1	3	4	1	3	1	-	-	-	2	1	-	-	-
OTHERS	3	1	1	2	3	3	1	3	-	2	-	2	2	1

SITE NO.	F23	F24	F25	F26	F27	F28	F29	FA1
NO. OF STONES	107	102	100	102	109	100	100	101
SILURIAN	90	94	94	91	59	69	65	100
BASALT	1	4	-	-	9	15	27	-
OLD RED SANDSTONE	7	1	4	8	4	2	1	-
VEIN ROCK	2	-	-	-	1	-	3	-
AGGLOMERATE	-	1	-	-	8	3	1	-
TRACHYTE	-	-	-	1	16	11	-	-
CARBONIFEROUS	-	-	-	-	-	-	-	-
CHEVIOT ANDESITE	-	-	-	-	-	-	-	-
OTHERS	1	-	2	-	4	-	3	-

SITE NO.	FA2	FA3	FA4	FA5	FA6	FA7	FA8	FA9	FA10	FA11	FA12	FA13	FA14
NO. OF STONES	110	110	106	105	103	107	105	108	107	111	108	106	103
SILURIAN	95	96	61	89	90	65	78	13	90	79	19	88	92
BASALT	-	-	33	4	3	23	15	85	2	10	75	4	1
OLD RED SANDSTONE	-	-	4	2	3	8	2	-	3	5	4	6	1
VEIN ROCK	3	4	2	3	3	2	3	2	2	4	-	2	-
AGGLOMERATE	1	-	-	-	-	-	-	-	1	-	1	-	5
TRACHYTE	-	-	-	-	-	-	-	-	2	-	-	-	1
CARBONIFEROUS	-	-	-	-	-	-	-	-	-	-	-	-	-
CHEVIOT ANDESITE	1	-	-	-	-	2	1	-	-	1	-	-	-
OTHERS	-	-	-	2	1	1	1	-	1	1	2	-	-

APPENDIX F.

RESULTS OF HEAVY MINERAL ANALYSES

Locations of samples illustrated are indicated in Appendix A, part 1. All samples are from the basal series.

Figures are expressed as percentages.

SAMPLE NO.	S.G.5	S.G.1	S.42	S.38	S.34	S.32	S.31
AUGITE	3.8	3.1	9.6	3.8	12.0	13.7	15.0
ENSTATITE	1.3	0.6	3.0	1.8	2.0	5.4	1.5
HYPERSTHENE	2.1	1.2	2.0	0.5	4.0	2.4	1.0
HORNEBLENDE	2.1	1.9	4.5	3.1	9.5	10.3	11.0
BIOTITE	11.7	16.9	11.6	16.3	10.0	9.8	2.5
MUSCOVITE	12.9	12.5	6.1	18.8	5.1	5.4	2.5
APATITE	1.3	0.6	3.0	2.5	3.0	4.4	5.0
CHLORITE	3,0	1.29	-	7.3	-	-	-
EIPDOTE	1.3	-	1.0	-	1.0	-	-
GARNET	5.6	11.3	8.8	3.8	5.5	4.9	1.0
RUTILE	1.3	-	0.5	1.0	1.0	1.0	2.5
TOURMALINE	7.4	6.9	1.0	1.2	0.5	0.5	1.0
ZIRCON	5.6	11.3	8.1	8.5	2.5	2.4	4.0
Fe MINERALS	37.0	28.5	37.4	28.0	40.0	32.9	50.0
SAMPLE NO.	S.30	S.28	S.23	S.15	S.10	S.4	S.1
AUGITE	16.7	15.1	11.1	6.6	5.2	2.9	7.2
ENSTATITE	2.5	4.6	2.9	3.2	2.6	-	0.5
HYPERSTHENE	0.6	0.9	0.9	0.7	1.1	-	0.9
HORNEBLENDE	12.4	8.7	8.6	2.8	8.4	9.1	7.2
BIOTITE	11.2	5.1	8.6	9.1	6.8	2.6	7.2
MUSCOVITE	2.5	3.7	2.9	11.3	7.3	3.6	8.6
APATITE	4.3	1.8	2.9	2.1	4.7	3.6	2.4
CHLORITE	-	-	1.4	-	-	-	-
EPIDOTE	1.9	-	0.9	3.9	2.1	-	-
GARNET	3.1	5.6	3.9	1.8	2.6	4.7	3.8
RUTILE	0.6	-	-	-	0.6	0.7	0.9
TOURMALINE	0.6	0.9	2.4	-	0.5	1.4	0.9
ZIRCON	3.0	3.7	2.9	4.6	7.3	8.4	3.4
Fe MINERALS	38.0	45.7	46.5	46.9	44.8	60.0	52.0

Olivine was found in samples 32 (2.9%), 34 (6.7%) and 42 (2.4%).

APPENDIX G.

DETAILS OF BASALT ERRATICS

IN SOME SAMPLES OF THE BASAL SERIES (CHAPTERS 1 and 3)

Sample locations are as illustrated in Appendix A, part 1.

Samples 1-29 lie down-glacier of the main body of the Kelso Lavas.

Samples 30-34 lie on the lavas.

Samples 35-42 lie up-glacier of the main lava body but immediately down-glacier of the East Gordon ridge, an "arm" of the lavas.

Samples S.X. to S.G.2 lie up-glacier of the lavas.

SAMPLE NO.	1	2	3	4	5	6	7	9	10	11	12	14	15	16	17	18	20	21	22	23
AVERAGE WEIGHT OF BASALT ERRATICS (gms)	13	82	102	55	67	36	65	74	31	38	17	26	71	26	14	26	16	31	63	49
NUMBER OF "WEATHERED" BASALTS	3	4	3	14	2	8	5	5	5	5	7	7	9	8	4	7	4	7	4	8
NUMBER OF "FRESH" BASALTS	4	3	8	1	3	4	5	3	1	3	4	3	8	4	6	4	1	6	12	6
AVERAGE WEIGHT OF WEATHERED BASALTS	13	88	89	58	45	28	32	79	32	32	21	31	39	32	13	28	16	32	8	68
AVERAGE WEIGHT OF FRESH BASALTS	13	75	107	20	82	54	98	67	30	62	13	15	108	14	12	24	16	30	82	24

SAMPLE NO.	24	25	26	27	28	29	30	31	33	34	35	36	37	38	39	40	41	42	X	G.1	G.2
AVERAGE WEIGHT OF BASALT ERRATICS (gms)	80	17	54	91	43	62	51	86	87	43	178	265	154	12	13	154	235	61	13	17	60
NUMBER OF "WEATHERED" BASALTS	12	12	36	16	33	21	30	36	41	48	5	7	-	3	4	3	20	3	1	-	2
NUMBER OF "FRESH" BASALTS	3	12	7	12	11	25	9	11	21	2	4	4	7	-	5	8	5	8	1	1	2
AVERAGE WEIGHT OF WEATHERED BASALTS	103	17	66	125	34	26	56	82	65	33	160	419	-	12	13	133	290	60	12	-	60
AVERAGE WEIGHT OF FRESH BASALTS	15	17	17	45	70	92	32	102	131	8	200	129	154	-	13	163	15	61	13	17	60

BIBLIOGRAPHY

AARTOLANTI, T. (1966) The Koijarri-Urjala drumlin field. Terra Vol. 78 pp 42-50.

ABBOTT, D. (1967) Heavy mineral analysis in glacial deposits of the Bathhurst area. Mining in Canada 1967, from Abstracts N. Am Geol. pp. 19-23.

ANDEL, T.H. Van (1959) Reflections on the interpretation of heavy minerals. J. Sedim. Petrol. Vol. 29 pp. 153-161.

ANDREWS, J.T. (1965) Surface boulder orientation studies around the north-western margin of the Barnes Ice Cap. J. Sedim. Petrol. Vol. 35 pp. 753-758.

ANDREWS, J.T. (1965) Glacial geomorphological studies on north-central Baffin Island, North West Territories, Canada. Ph.D. Thesis (2 vols.) Univ. of Nottingham.

ANDREWS, J.T. (1971) Methods in the Analysis of till fabrics. Till - a symposium Ed. R.P. Goldthwaite. Ohio State Univ. Press.

ANDREWS, J.T. and KING, C.A.M. (1968) Comparative till fabrics and till fabric variability in a till sheet and a drumlin: a comparative study. Proc. Yorks. Geol. Soc. Vol. 36 pp. 453-464.

ANDREWS, J.T. and SHIMUZU, K (1966) Three dimensional vector technique for analysing till fabrics. Geogrl. Bull. Vol.8 pp. 151-165

ARANOW, S (1959) Drumlins and related streamline features in the Warwick-Tokio area, N. Dakota. Am. J. Sci. Vol. 257 pp. 191-203.

ARNEMAN, H.F. and WRIGHT, H.E. (1959) Petrography of some Minnesota tills. J. Sedim. Petrol. Vol. 29 pp. 540-544.

BEAUMONT, P. (1971) Stone orientation and stone-count data from the lower till sheet, East Durham. Proc. Yorks. Geol. Soc. Vol. 38 pp. 357-372.

BOULTON, G.S. (1970) On the deposition of sub-glacial and melt-out tills on the margins of certain Svalbard glaciers. J. Glaciol. Vol. 9 pp 231-245.

BOULTON, G.S. (1971) On the origin and transport of englacial debris in Svalbard glaciers. J. Glaciol. Vol. 10 pp. 391-412

BOULTON, G.S. (1971a) Till genisis and fabric in Svalbard in Till-a syposium. Ed. R.P. Goldthwaite. Ohio State Univ. Press. pp. 41-72.

BOULTON, G.S. (1972) Lecture to post-grad research group, Univ. of Edinburgh. December, 1972.

BOULTON, G.S. (1975) Processes and patterns of subglacial sedimentation: a theoretical approach in Ice Ages: Ancient and Modern Ed. A.E. Wright and F. Mosely. pp. 7-42.

BOULTON, G.S. (1976) The origin of glacially fluted surfaces - observations and theory. J. Glaciol. Vol. 17 pp. 421-433

BOULTON, G.S. and DENT, D.L. (1974) The nature and rates of post-depositional changes in recently deposited till. Geogr. Annlr. Vol. 56 pp. 224-234.

BUDD, W.F. (1970) Ice flow over bedrock perturbations. J. Glaciol. Vol. 9 pp. 151-165.

BUDD, W.F. (1971) Stress variations with ice flow over undulations. J. Glaciol. Vol. 10 pp. 380-390.

CAROL, H. (1947) The formation of roches mountonnees. J. Glaciol. Vol. 1 pp. 57-62.

CARRUTHERS, R.G. (1947) The secret of the glacial drifts. Proc. Yorks. Geol. Soc. Vol. 27 pp. 43-57.

CARRUTHERS, R.G. (1944) The secret of the glacial drifts, part II - applications to Yorkshire. Proc. Yorks. Geol. Soc. Vol. 27 pp. 129-172.

CARRUTHERS, R.G., et al. (1930) The geology of the Alnwick District. Mem. Geol. Surv. U.K. H.M.S.O.

CARRUTHERS, R.G. (1939) On northern glacial drifts : some peculiarities and their significance. Q. Jl. Geol. Soc. Lond. Vol. 379 pp. 299-333.

CARRUTHERS, R.G., et al.(1932) The geology of the Cheviot Hills. Mem. Geol. Surv. U.K. H.M.S.O.

CATT, J.A. and PENNY, L.F. (1966) The Pleistocene desposits of Holderness. Proc. Yorks. Geol. Soc. Vol. 35 pp. 357-372.

CHARLESWORTH, J.K. (1926a) The glacial geology of the S. Uplands, west of Annandale and upper Clydeside. Trans. Roy. Soc. Edinb. Vol. 55 pp. 1-23.

CHARLESWORTH, J.K. (1926b) The re-advance marginal kame moraine of the South of Scotland and some later stages of retreat. Trans. Roy. Soc. Edinb. Vol. 55 pp. 25-50

CHORLEY, R.J. (1959) The shape of drumlins. J. Glaciol. Vol. 3 pp. 339-344

CHORLEY, R.J. and HAGGET, P. (1965) Trend surface mapping in geomorphological research. Trans. Inst. Br. Geogr. Vol. 37 pp. 47-65.

CLAPPERTON, C.M. (1967) The de-glaciation of part of the East Cheviot area. Ph.D. Thesis University of Edinburgh 1967.

CLAPPERTON, C.M. (1968) Channels formed by super-imposition of glacial meltwater streams, with special reference to the E. Cheviot hills. Geogr. Annir. Vol. 50 pp. 4-41

CLAPPERTON, C.M. (1970) The evidence for a Cheviot ice cap. Trans. Inst. Br. Geogr. Vol. 50 pp. 115-127

CLAPPERTON, C.M. (1971) The location and origin of glacial meltwater phenomena in the eastern Cheviot hills. Proc. Yorks, Geol. Soc. Vol. 38 pp. 332-344.

CLAPPERTON, C.M. (1975) The debris content of surging glaciers in Svalbard and Iceland. J Glaciol Vol. 14 pp. 395-407.

CONNALLY, G.G. (1964) Garnetratios and provenance in the glacial drift of western New York. Science Vol. 144 pp. 1452-1453.

CORTE, A. (1966) Particle sorting by repeated freezing and thawing. Science Vol. 142 pp. 499-508.

CRAMPTON, C.B. (1959) Analysis of heavy minerals in certain drift soils of Yorkshire. Proc. Yorks. Geol. Soc. Vol. 32 pp. 174-180.

CRAMPTON, C.B. (1958) Heavy minerals in the magnesian limestone of Yorkshire. Proc. York. Geol. Soc. Vol. 31 pp. 383-390

CURRAY, J.R. (1956) The analysis of two-dimensional orientation data. J. Glaciol. Vol. 64 pp. 117-131.

DONOVAN, C. and JAMES, M. (1967) Geochemical dispersion in glacial overburden over the Tynagh bare metal deposits, west-central Eire. Can. Geol. Surv. Paper 66-54 pp. 80-110.

DOORNKAMP, E. and KING, C.A.M. (1971) Numerical analysis in geomorphology. publ. Edward Arnold, London, 1971.

DRAKE, L.D. (1971) Evidence for ablation and basal till in east-central New Hampshire. in Till - a syposium. Ed. R.P. Goldthwaite. Ohio State Univ. Press.

DRAKE, L.D. (1974) Evidence for fabric control by clast-shape. Bull. Geol. Soc. Am. Vol. 85 pp. 247-250

DREIMANIS, A and REAVELY, G.H. (1953) Differentiation of the lower and the upper till along the N. shore of Lake Erie. J. Sedim. Petrol. Vol. 23 pp. 238-259.

DREIMANIS, A. and VAGNERS, U.G. (1971) Bimodal distribution of rock and mineral fragments in basal tills. in Till - a syposium. Ed. R.P. Goldthwaite. Ohio State Univ. Press.

DREIMANIS, A. and VAGNERS, U.G. (1969) The lithological relationship of till to bedrock. Quatemary Geology and Climate. Vol. 16 Proc. VII Congress Int Assocn Quat. Research.

DYLIK, J. (1967) Solifluction, congelifusion and related slope processes. Geogr. Annalr. Vol. 49A pp. 167-177.

DYSON, J.L. (1952) Ice-ridged moraines and their relation to glaciers. Am. J.Sci. Vol. 250 pp. 204-211

ECKFORD, R.J.A., RICHIE, M. and BALSILLIE, J. (1930) The lavas of Tweedale and their position in the Carboniferous sequence. Sum. Prog. Geol. Surv. 1930

ECKFORD, R.J.A. and RICHIE, M. (1939) The igneous rocks of the Kelso district. Trans. Edinb. Geol. Soc. Vol.XIII pp. 342-365.

ELDER, S., McCALL, R.J.S. and NEAVES, W.D. (1935) The drumlins of Glasgow. Trans. Geol. Soc. Glasg. Vol. XIX pp. 219-240.

EMBLETON, C. and KING, C.A.M. (1969) Glacial and Periglacial Geomorphology Edward Arnold 1969.

EMBLETON, C. and KING, C.A.M. (1975) Glacial Geomorphology Edward Arnold 1975.

EMBLETON, C. and KING, C.A.M. (1975) Periglacial Geomorphology Edward Arnold 1975.

ERIKSSON, K. (1973) The distribution of some metals in different till fractions. Bull. Geol. Inst. Uppsala. Vol. 5 pp. 157-164.

EVENSON, E.B. (1971) The relationship of macro- and micro-fabric of till and the genisis of glacial land forms in Jefferson County Wisconsin. in Till - a symposium. Ed. R.P. Goldthwaite. Ohio State Univ. Press.

FITZPATRICK, E.A. (1963) Deeply weathered rock in Scotland, its occurrence, age and contribution to soils. J. Soil Sci. Vol. 14 pp. 33-43.

FLINT, R.F. (1949) Leaching of carbonates in glacial drift and loess as a basis for age correlation. Mem. U.S. Geol. Surv. Vol. 45 pp. 297-311.

FOLLESTAD, B.A. (1973) Beskrevelske til kvartaerges logisk kart 1916 I - M 1:50,000. Norges Geologiska Undersøkelse Vol. 296 pp. 2-41.

FOWLER, A. and McGREGOR, A.G. (1937) The Kelso District. Sheet 25. Sum. Prog. Geol. Surv. 1937

GILLBERG, G. (1964) Till distribution and ice movement on the northern slopes of the South Swedish Highlands. Geol. Foren Forhandl Vol. 86 pp. 88-97.

GILLBERG, G. (1965) A statistical study of till from Sweden. Geol. Foren Forhandl Vol. 87 pp. 182-193.

GILLBERG, G. (1967) Further discussion of the lithological homogenity of till. Geol. Forn Forhandl Vol. 89 pp. 321-332.

GILLBERG, G. (1967) Distribution of different limestone material in till. Geol. Foren Forhandl Vol. 89 pp. 372-381

GILLBERG, G. (1968) Lithological distribution and homogeneity of glacio-fluvial material. Geol. Foren Forhandl Vol. 90 pp. 421-443.

GJESSING, J. (1966) On plastic scouring and sub-glacial erosion. Nor. Geogr. Tidsskr. Vol. XX pp. 1-35.

GLEN, J.N., DONNER, J.J. and WEST, R.G. (1957) On the mechanism by which stones in till become orientated. Am. J. Sci. Vol. 255 pp. 194-205.

GLUCKERT, J (1973) Two large drumlin fields in C. Finland. Fennia. Vol. 120 pp. 5-37.

GLUCKERT, J. (1973) The Kinisano drumlin field, N. Finland. Bull. Geol. Soc. Finl. Vol. 46 pp. 37-42.

GOLDTHWAITE, R.F. (1958) Wisconsin Age Forests in W. Ohio, 1 : Age and glacial events. Ohio J. Sci. Vol. 58 pp. 208-220.

GOLDTHWAITE, R.P. (Ed.) etaal. (1971) Till - A Symposium. Ed. R.P. Goldthwaite. Ohio State Univ. Press 1971.

GOODCHILD, J.C. (1875) Glacial phenomena of the Eden Valley. Q. Jl. Geol. Soc. Lond. Vol. XXXI pp. 55-63.

GOODCHILD, J.C. (1904) The geological history of lower Tweedside. Proc. Geol. Ass. Vol. XVIII pp. 105-142.

GRAVENOR, C.P. (1955) The origin and significance of prairie mounds. Am. J. Sci. Vol. 253 pp. 475-481.

GRAVENOR, C.P. (1958) The origins of drumlins. Am. J. Sci. Vol. 251 pp. 674-681.

GRAVENOR, C.P. (1974) The Yarmouth drumlin field, Nova Scotia. J. Glaciol. Vol. 13 pp. 121-135.

GRAVENOR, C.P. and KUPSCH, W.C. (1959) Ice disintegration features in N. Canada. J. Geol. Vol. 67 pp. 48-64

GRAVENOR, C.P. and MENLEY, W.A. (1958) Glacial flutings in central and northern Alberta. Am. J. Sci. Vol. 256 pp. 715-728

GRAVENOR, C.P. and STUPAVSKY, K. (1974) Magnetic susceptibility of the surface tills of southern Ontario. Can. J. Earth Sci. Vol. II pp- 658-663.

GREEN, R. (1964) Available methods for analysis of vertical data. J. Sedim. Petrol. Vol. 34 pp. 440-442.

GREGORY, S. (1964) Statistical methods and the geographer. Longmanns, Green and Co. Ltd., 1964.

GIBSON, P.W.F. (1964) Recession of glacier Tasissarssik, East Greenland. J. Glaciol. Vol. 7 pp. 361-363.

GROSS, D.L. and MORAN, S.R. (1971) Grain size and mineralogical gradations within tills of the Allegheny plateau. in Till - a symposium. Ed. R.P. Goldthwaite.

GUNN, W. and CLOUGH, C.T. (1895) The geology of part of Northumberland including the country between Wooler and Coldstream. Mem. Geol. Surv. U.K. H.M.S.O.

HAEFELI, R. (1964) Some observations on glacier flow. J. Glaciol. Vol. 7 pp. 490-498.

HARRINGTON, H.J. (1962) Glacier wasting and retreat in the S. Alps of New Zealand. J. Glaciol. Vol. 2 pp. 140-145.

HARRIS, S.A. (1967) Origin of part of the Guelph drumlin field and the Gaull and Paris moraines, Ontario - a re-interpretation. Canadian Geographer Vol. 9(1) pp. 16-34.

HARRIS, S.A. (1972) The nature and use of till fabrics in Research Methods in Pleistocene Geomorphology. Eds. Yatsen, E. and Falconer, A. pp. 45-65.

HARRISON, P.W. (1957) A clay-till fabric; its character and origin. J. Geol. Vol. 65 pp. 275-308.

HARTSHORN, J.H. (1958) Flowtill in south eastern Massachusetts. Bull. Geol. Soc. Am. Vol. 60 pp. 477-482.

HILL, A.R. (1968) An experimental test of the field technique of till macrofabric analysis. Trans. Inst. Br. Geogr. Vol. 45 pp. 93-105.

HILL, A.R. (1973) The distribution of drumlins in Co. Down, Ireland. Ann. Ass. Am. Geogr. Vol. 63 pp. 226-240

HINXMAN, L.W. et al. (1923) The geology of Corrour and the moor at Rannoch. Mem. Geol. Surv. U.K. 1923.

HOLDESWORTH, J. (1973) The Barnes Ice Cap and englacial debris in glaciers. J. Glaciol. Vol. 12 pp. 147-148.

HOLLINGWORTH, S.E. (1931) The glaciation of W. Edenside and adjoining areas and the drumlins of Edenside and the Solway basin. Q. J. Geol. Soc. Lond. Vol. 87 pp. 281-359.

HOLMES, C.D. (1941) Till fabric. Bull. Geol. Soc. Am. Vol. 52 pp. 1299-1354.

HOLMES, C.D. (1960) The evolution of till stone shapes in central New York. Bull. Geol. Soc. Am. Vol. 71 pp. 423-441.

HOPKINS, A. (1852) On the granite blocks of the S. Highlands of Scotland. Q. J. Geol. Soc. Lond. Vol. 8 pp. 22-30.

HOPPE, G. (1952) Hummocky moraine regions with special reference to the interior of Norrbottn. Geogr. Annlr. Vol. 34 pp. 1-71

HOPPE, G. (1957) Problems of Glacial morphology and the Ice Age. Geogr. Annlr. Vol. 39 pp. 1-17

HOPPE, G. (1963) Subglacial sedimentation with examples from N. Sweden. Geogr. Annlr. Vol. XLV pp. 41-51.

HOPPE, G. and SCHYTT, V. (1953) Some observations on fluted moraine surfaces. Geogr. Annlr. Vol. 35 pp. 105-115.

HORNE, J. (1899) The inter-crossing of boulders in the Applecross mountains. Trans. Edinb. Geol. Soc. Vol. 7 pp. 38-44.

HYYPPA, E. (1945) Tracing the source of the pyrite stones from Vihanti on the basis of glacial geology. Lecture of Geol. Soc. Finl No. 142.

IRANI, R.R. and CLAYTON, F.C. (1963) Particle size; measurement, interpretation and application. Publ. Wiley (N.Y.) 165pp 1963.

IRVING, J. (1930) Four felstone intrusions in central Berwickshire. Geol. Mag. Vol 11 pp. 529-538.

IVES, J.D. (1964) Indications of recent extensive glacierization in north central Baffin Island. J. Glaciol. Vol. 7 pp. 497-502.

JARNEFORS, B. (1952) A Sediment - petrographic study of till from the Pajala district N. Sweden. Geol. Foren Forhandl. Vol. 74 (2) pp. 185-209.

KAISER, R.F. (1962) Composition and origin of glacial till, Mexico and Kosoag quadrangles, New York. J. Sedim. Petrol. Vol. 32 (3) pp. 502-513.

KAMB, B and LA CHAPELLE, E. (1964) Direct observations of glacier sliding over bedrock. J. Glaciol Vol. 5 pp. 160-172.

KAURANNE, L.K. (1960) A statistical study of stone orientation in glacial till. Suom Geol Su. No. 32 Geol Sal. Finl. pp. 89-98.

KELLY, T.E. and BAKER, C.H. (1966) Colour variations within glacial till, east-central North Dakota. J. Sedim. Petrol. Vol. 36 pp. 75-80.

KERR, P.F. (1959) Optical Mineralogy Publ. McGraw-Hill. 452 p.

KING, C.A.M. and BUCKLEY, J.T. (1968) The analysis of stone size and shape in Artic environments. J. Sedim. Petrol. Vol. 38 pp. 200-214.

KIRBY, R.P. (1969) Variations in glacial deposition in a sub-glacial environment an example from Midlothian. Scott. J. Geol. Vol. 5 pp. 49-53.

KIRBY, R.P. (1969) Morphometric analysis of glaciofluvial terraces in the Esk basin. Trans. Inst. Br. Geogr. Vol. 48 pp. 35-46

KRUGER, J. (1973) Operator variance in orientation measurements in till macrofabric analyses. Bull Geol. Inst, Uppsala. Vol. 15 pp. 117-125.

KUMBEIN, W.C. (1939) Preferred orientation of pebbles in sedimentary deposits. J. Geol. Vol. 47 pp. 160-172.

KUPSCH, W.C. (1955) Drumlins with jointed boulders near Dollard, Saskatchewan. Bull Geol. Soc. Am. Vol. 66 pp. 327-338.

KUPSCH, W.C. (1962) Ice-thrust ridges in W. Canada. J. Geol. Vol.70 pp. 582-594.

KYNASTON, D.A. et al (1908) The geology of the country near Oban and Dalmally. Mem. Geol. Surv. U.K. 1908

LEMKE, R.W. (1958) Narrow linear drumlins near Velva, N. Dakota. Am. J. Sci. Vol. 256 pp. 270-284.

LEWIS, W.V. (1954) Pressure release and glacial erosion. J. Glaciol. Vol. 4 pp. 102-113.

LINEBACK, J.A. (1971) Pebble orientation and ice movement in south-central Illinois. in Till - a symposium Ed. R.P. Goldthwaite. pp. 328-334.

LUNDQVIST, G. (1935) Blockunder sokningar historik och metodik. Sver. Geol. Unders. Afh. Vol. 390 pp. 3-45.

McARTHUR, J.L. (1972) Comparison of two British Standard tests for the determination of particle-size distribution. Area. Vol. 4 pp. 1-12.

McGREGOR, A.G. and ECKFORD, R.J.A. (1948) The upper Old Red Sandstone and Lower Carboniferous sediments of Teviotdale and Tweedside and the stones of the abbeys of the Scottish Borderland. Trans. Edinb. Geol. Soc. Vol. 14 pp. 230-245.

MacLINTOCK, P. and DREIMANIS, A. (1964) Re-orientation of till fabric by over-riding glacier in the St. Lawrence Valley. Am. J. Sci. Vol. 262 pp. 133-142.

McROBERT, Lady R.W. (1914) Acid and intermediate intrusions and associated ash necks in the neighbourhood of Melrose. Q. Jl. Geol. Soc. Lond. Vol. LXX pp. 303-320.

MANSON, W. (1933) On a boring for water at Stonefold Farm, Berwickshire. Sum. Prog. Geol. Surv. 1933.

MANSON, W. and ECKFORD, R.J.A. (1927) Notes on a Xenolith in reibeckite-trachyte, mid-Eildon. Trans. Edinb. Geol. Soc. Vol. XII pp. 143-152.

MARCUSSEN, I. (1973) Stones in Danish tills as a stratigraphical tool. Bull. Geol. Inst. Univ. Uppsala. Vol. 5 pp. 177-181.

MARK, D.M. (1973) Analysis of axial orientation data, including till fabric. Bull Geol. Soc. Am. Vol. 84 pp. 1369-1373.

MICKELSON, D.M. (1971) The glacial geology of the Borrough's glacier area, S. Alberta. Inst. Polar Stud. Report 40 pp. 1-18

MICKELSON, D.M. (1973) The nature and rate of basalt till deposition in a stagnating ice mass, Burrough's glacier, Alaska. Artic and Alpine Research Vol. 5 pp. 17-27.

MILLER, J.W. (1972) Variations in New York drumlins. Ann. Ass. Am. Geogr. Vol. 63 pp. 226-240.

MORGAN, A.V. (1973) The Pleistocene geology of the area N and W of Wolverhampton. Phil. Trans. R. Soc. Vol. 13 pp. 233-297.

MUIR, J.W. et al (1956) The soils of the country around Jedburgh and Morebattle. Mem. Soil. Surv. Scotland H.M.S.O. 1956.

MORAN, S. (1971) Glaciotectonic structures in till. in Till- A Symposium Ed. R.P. Goldthwaite.

MUIT, R.O. (1958) Ph.D. Thesis University of Edinburgh. Petrology and sedimentation of the Millstone Grit of Scotland.

NEIHEISEL, J. (1963) Heavy mineral investigation of recent and Pleistocene sands of the lower coastal plain of Georgia. Bull. Geol. Soc. Am. Vol. 73 pp. 156-181.

NOBLES, L.H. and WEERTMAN, J. Influence of irregulatities of the bed of an ice-sheet on the deposition rate of till. in Till - A Symposium. Ed. R.P. Goldthwaite.

NYE, J.F. (1952) The mechanics of glacier flow. J. Glaciol. Vol. 2 pp. 82-93.

NYE, J.F. (1952) Glacier Mechanics. J. Glaciol. Vol. 2 pp. 91-93.

NYE, J.F. (1959) The motion of ice sheets and glaciers. J. Glaciol. Vol. 2 pp. 493-507.

ORME, A.R. (1967) Drumlins and the Weichel,glaciation of Connemara. Irish Geog. Vol. 5 pp. 262-274.

OSTRY, R.C. and DEANE, R.F. (1963) Microfabric analyses of till. Geol. Soc. Am, Bull. Vol. 74 pp. 165-168.

PATERSON, W.S.B. (1970) The sliding velocity of the Athabaska glacier. J. Glaciol Vol. 9 pp. 171-183.

PATERSON, W.S.B. (1971) Temperature measurements in Athabaska glacier, Alberta, Canada. J. Glaciol Vol. 10 pp. 201-217.

PEACH, A.M. (1909) Boulder distribution from Lennoxtown, Scotland. Geol. Mag. Vol. 46 pp. 26-31.

PEACH, A.M. and HORNE, J. (1899) The Silurian rocks of Britain Vol. 1 Scotland. Mem. Geol. Surv. U.K. H.M.S.O. 1899.

PENNY, L.F. (1964) A review of the last glaciation in Great Britain. Proc. Yorks. Geol. Soc. Vol. 34 pp. 387-411.

PENNY, L.F. and CATT, J.A. (1967) Stone orientation and other structural features of tills in E. Yorkshire. Geol. Mag. Vol. 104 pp. 344-360.

PESSL, F. Junr. (1971) Till fabrics and till stratigraphy in Western Connecticutt. in Till - A Symposium Ed. R.P. Goldthwaite Ohio State Univ. Press.

PETTERSSON, M. (1968) Indications of provenance in some Anglesey drift soils. J. Soil Sci. Vol. 19 (1) pp. 31-43.

PRICE, R.J. (1973) Glacial and fluvioglacial landforms. Oliver and Boyd Edinburgh, 1973.

PRINGLE, J. (1948) (1961 Impression) The South of Scotland. British Regional Geology. H.M.S.O. 1948.

RAGG, J.M. et al (1960) The soils around Kelso and Lauder. Mem. Geol. Surv. U.K. 1960 H.M.S.O.

RAGG, J.M. and BIBBY, J.S. (1966) Frost weathering and solifluction deposits in Southern Scotland. Geogr. Annlr. Vol. 48A pp. 12-23.

RAYMOND, C.F. (1971) Flow in a transverse section of the Athabaska glacier, Alberta Canada. J. Glaciol. Vol. 10 pp. 160-171

REED, B. et al (1962) Some aspects of drumlin geometry. Am. J. Sci. Vol. 260 pp. 200-210.

RIN, I.J. (1972) A note on boulder trains from the Røros district. Norges Geol. Unders. Vol. 277 pp. 17-18.

ROSE, J. (1974) Small scale variability of some sedimentary properties of lodgement till and slumped till. Proc. Geol. Ass. Lond. Vol. 85 pp. 239-258.

ROSE, J. and LETZER, J.M. (1975) Drumlin measurement - a test of the reliability of data derived from 1:25,000 scale topographic maps. Geol. Mag. Vol. 112 pp. 361-371.

RUTLEY, (1962) Elements of Mineralogy (H.H. Read, 1962) Publ. Allan and Unwin. 525 pages.

SHAW, J. (1971) Mechanism of till deposition related to thermal conditions in a Pleistocene glacier. J. Glaciol Vol. 10 pp. 218-227.

SHAW, J. and FRESCHAUF, R.C. (1973) A kinematic discussion of the formation of glacial flutings. Can. Geogr. Vol. 17 pp. 19-35.

SHILTS, W.W. (1973) Glacial dispersal of rock minerals and trace elements in Wisconsin till. Geol. Soc. Am. Mem. Vol. 136 pp. 189-219.

SHOTTON, F.W. (1965) Normal faulting in British Pleistocene deposits. Q. Jl. Geol. Soc. Lond. Vol. 121 pp. 419-433.

SISSONS, J.B. (1967) The Evolution of Scotland's scenery Oliver and Boyd, Edinburgh, 1967.

SISSONS, J.B. (1974) The Quaternary in Scotland : A Review Scott. J. Geol. Vol. 10 (4) pp. 311-337.

SITLER, R.F. and CHAPMAN, C.A. (1955) Microfabrics of till from Ohio and Pennsylvania. J. Sedim. Petrol. Vol. 25 pp. 262-269.

SMALLEY, I.J. and UNWIN, D.J. (1968) The formation and shape of drumlins and their distribution and orientation in drumlin fields. J. Glaciol Vol. 7 pp. 377-390.

SMITH, W.W. (1962) Weathering on some Scottish basic igneous rocks with reference to soil formation. J. Soil Sci. Vol. 13 pp. 202-215.

SOUCHEZ, R.A. (1971) Ice-covered moraines in S.W. Ellesmere Island. Artic and Alpine Research 5 pp. 17-27.

STALKER, A. (1960) Ice-pressed drift forms and associated deposits in Alberta. Bull. Geol. Surv. Canada Vol. 57 pp. 1-38.

STALKER, A. (1973) Superficial geology of the Drumheller area, Alberta. Can. Geol. Surv. Mem. 370 pp. 1-122.

STEINMETZ, R. (1962) Analysis of vectorial data. J. Sedim. Petrol. Vol. 32 (4) pp. 801-812.

SWINZON, G.K. (1962) Investigation of shear zones in the ice sheet margin, Thule area, Greenland. J. Glaciol Vol. 4 pp. 215-219.

TIVY, J. (1962) An investigation of certain slope deposits in the Lowther hills. Trans. Inst. Br. Geogr Vol. 30 pp. 59-74.

TOMKEIFF, S.I. (1937) The petrochemistry of the Scottish Carboniferous and Permian igneous rocks. Bull. Volcan. 1937 Ser. II Vol. 1

TOMKEIFF, S.I. (1948) The petrology of the Scottish Carboniferous rocks of the Tweed basin. Trans. Edinb. Geol. Soc. Vol. 14 pp. 211-228.

TOMKEIFF, S.I. (1953) The Carboniferous igneous rocks of the Kelso district. Proc. Univ. D. Phil. Soc. Vol. XI pp. 7-17.

TRENHAILE, A.S. (1975) The morphology of a drumlin field. Ann. Assoc. Am. Geogr. Vol. 65 pp. 347-365.

VERNON, P. (1966) Drumlins and Pleistocene ice flow over the Ards peninsula, Strangford Lough area, Co. Down. J. Glaciol. Vol. 16 pp. 401-409.

WALTON, E.R. (1965) The Silurian greywackes in Peebleshire. Proc. R. Soc. Edinburgh. Vol. 65 pp. 411-429.

WATT, J.F. (1963) Sedimentary studies of the Old Red Sandstone of Berwickshire and East Lothian. Ph.D. Thesis, Univ. of Edinb. 1963.

WEERTMAN, J. (1957) On the sliding of glaciers. J. Glaciol. Vol. 3 pp. 33-39.

WEERTMAN, J. (1964) The theory of glacier sliding. J. Glaciol. Vol. 3 pp. 287-303.

WEERTMAN, J. (1966) Effect of a basal water layer on the dimensions of ice sheets. J. Glaciol. Vol. 6 pp. 191-207.

WEST, R.G. and DONNER, J.J. (1956) The glaciation of East Anglia and the East Midlands. Q. Jl. Geol. Soc. Lond. Vol. 12 pp. 69-91.

WRIGHT, H.E. (1957) Stone orientation in the Wadena drumlin field, Minnesota. Geogr. Annlr. Vol. 39 pp. 19-31.

WRIGHT, H.E. (1962) Role of the Wadena lobe in the Wisconsin glaciation of Minnesota. Geol. Soc. Am. Bull. Vol. 73 pp. 73-100.

YOUNG, J.A.T. (1969) Variations in till macrofabric over very short distances. Geol. Soc. Am. Bull. Vol. 80 pp. 2343-2352.